Can Languages and Tools Produce Better Software?

- In this talk, better means more reliable
  - Less likely to fail

SPT Approach

- Redundency is good
- Redundancy exposes inconsistency

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SPT Approach

- Redundency is good
- Redundancy exposes inconsistency
- Inconsistency points to errors
- Compare what programmer should do against what code does

Lightweight Specifications

- Start with description of correct/incorrect behavior
  - Not total specification ⇒ not total correctness
- Programmers provide specs
- Tools reward additional effort
  - Mechanically and systematically find errors

Programmers Write Types

- Successful, wide accepted specifications
  - Programmers understand and write type declarations
  - Declarations aid comprehension
  - Type checking is fast, routine, and finds errors
- Serve several roles
  - Documentation of interface syntax
  - Basis for program abstractions
  - Static (compile-time) error detection

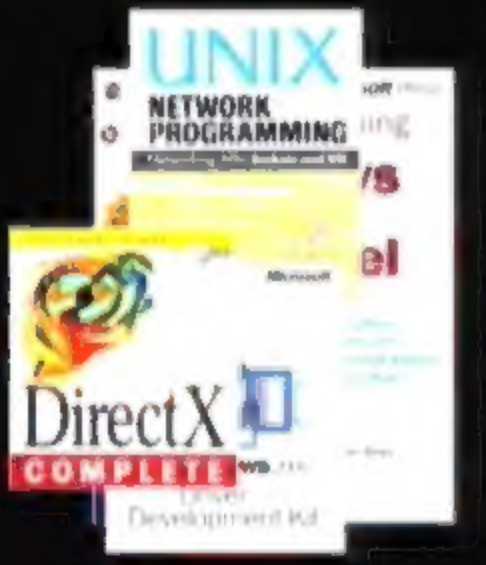
Extend Successful Approach

- Specify and check other program properties
  - Languages (programming and domain-specific) express properties
  - Tools check that code obeys rules
- Goal is partial correctness
  - Detect and report important classes of errors
  - No guarantee of program correctness
- Systematic
  - Sound, complete analysis can flag absence of errors

SPT Overview

- Reliable interfaces
  - Vault
  - SLAM
  - ESP
- Concurrency and security
  - Behave!
  - Golf

Interfaces Have Usage Rules



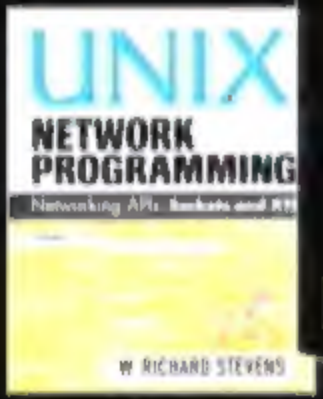
- Specs in documentation
  - Incomplete, unenforced, wordy
  - Order of operations & data access
  - Resource management
- Disobeying rules causes bad behavior
  - System crash or deadlock
  - Unexpected exceptions
  - Failed runtime checks
  - Security flaws

Example Usage Rule: Sockets

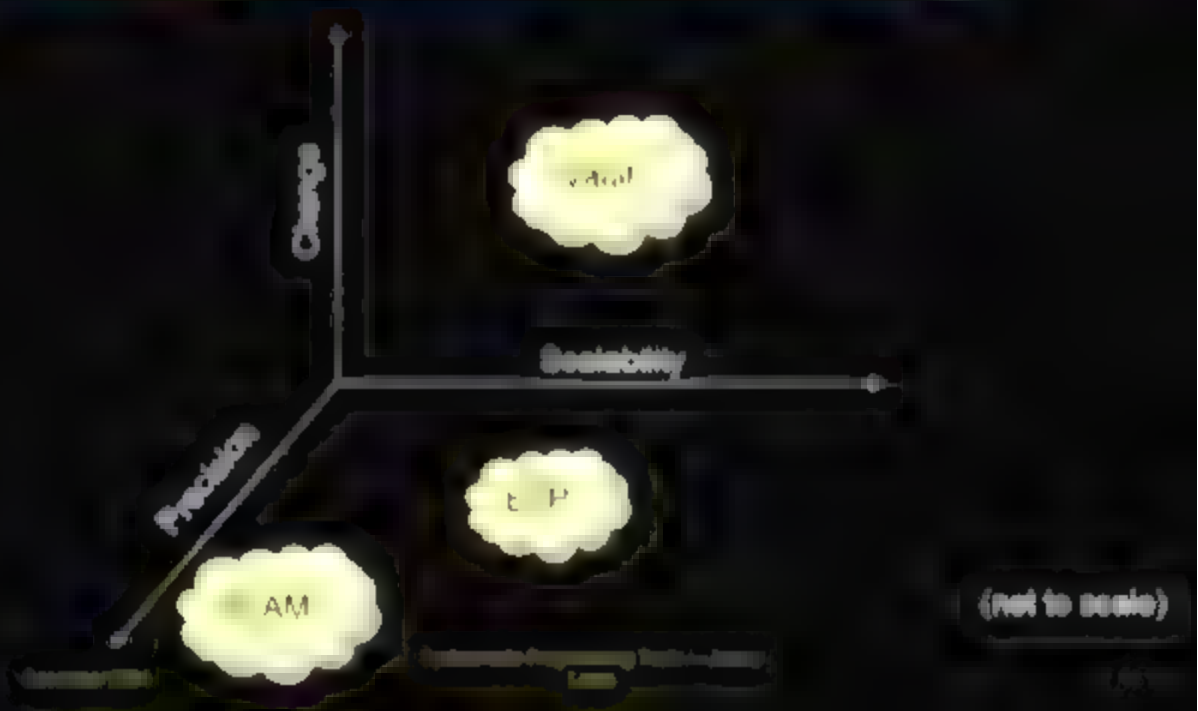
the "communication domain" in which communication is to take place; see protocols(5).

Sockets of type SOCK_STREAM are full-duplex byte streams, similar to pipes. A stream socket must be in a connected state before any data may be sent or received on it. A connection to another socket is created with a connect(2) call. Once connected, data may be transferred using read(2V) and write(2V) calls or some variant of the send(2) and recv(2) calls. When a session has been completed a close(2V), may be performed. Out-of-band data may also be transmitted as described in send(2) and received as described in recv(2).

The communications protocols used to implement a SOCK_STREAM insure that data is not lost or duplicated. If a piece of



SPT Specification & Checking



SPT Overview

- Reliable interfaces
  - Vault
  - SLAM
  - ESP
- Security and concurrency
  - Behavel
  - Golf

Vault (Rob DeLine, Manuel Fähndrich)

- Vault folds usage rules into programming language's type system
  - Interface author states rules in type signature
  - Compiler rejects client code that violates rule (type error)
  - Every violation guaranteed to be found (soundness)

Why a Type-based Approach?

- Types are widely accepted form of specification
- Specification and code are kept in sync
- Developers find and fix bugs before execution
- Programmers understand violations and how to fix them
- Efficient, scalable analysis doesn't slow development

Tracked Types and Keys

- Usage rules talk about individual objects

```
void listen (tracked(S) sock, int)   [ S @ named => listening ]
```

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void listen (tracked(S) sock, int)   [ S @ named -> listening ]
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- Naming: tracked types give compile-time names (keys) to objects

Tracked Types and Keys

- Usage rules talk about individual objects

```
void listen (tracked(S) sock, int)  [ S @ named -> listening ]
```

- Naming: tracked types give compile-time names (keys) to objects
- Object state: key can have symbolic state to model state of object

Tracked Types and Keys

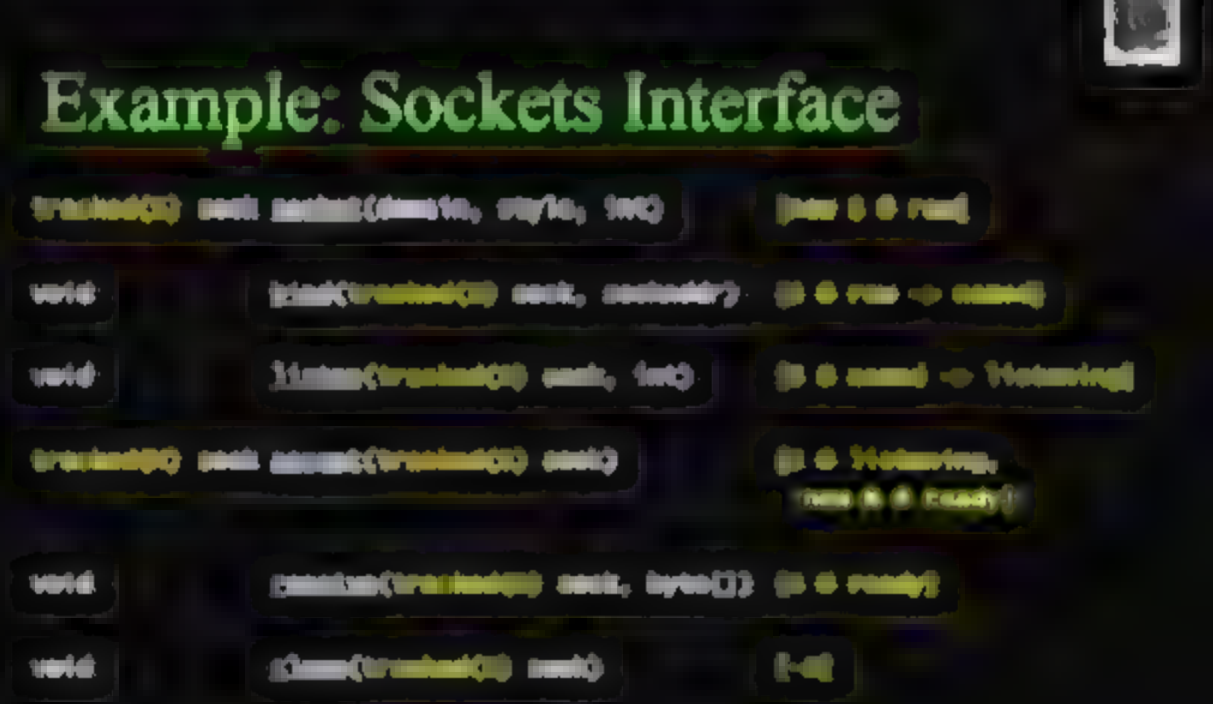
- Change specs combine pre/post condition for functions

Tracked Types and Keys

- Change specs combine pre/post condition for functions
- Add key:
  - `tracked(s) sock socket (...) [ new s @ raw ]`
- Consume key:
  - `void close (tracked(s) sock) [ -s ]`
- Change key state:
  - `void bind (tracked(s) sock) [ s @ raw -> named]`

Example: Sockets Interface

Example: Sockets Interface



Statically Enforcing Usage Protocols

- At every program point, Vault compiler computes key set
  - Functions and built-in operations (new/free) change key set
  - Key must be consumed, not "leaked"
- On each path in function's body, check:
  - Pre-condition transformed into post-condition
  - All proof obligations satisfied
    - Pre-conditions of other function calls
    - Primitive operations (memory access, free)
- Avoid exponential blow-up
  - Require uniform predicate at join points

Checking Socket Client Code

```
void communicate(sockaddr addr) {
  [illegible] sock s = socket('[illegible]', '[illegible]', 0);
  bind(s, addr);
  listen(s, 0);
  while (![illegible]()) {
    [illegible] sock c = accept(s);
    receive(s, buffer);
    close(c);
  }
  close(s);
}
```

Checking Socket Client Code

Checking Socket Client Code

```
void communicate(sockaddr addr) {
  [redacted] sock = socket(AF_INET, SOCK_DGRAM, 0);
  bind(s, addr);
  listen(s, 0);
  while (!shutdown()) {
    [redacted] sock c = accept(s);
    receive(s, buffer);
    close[redacted];
  }
  close(s);
}
```

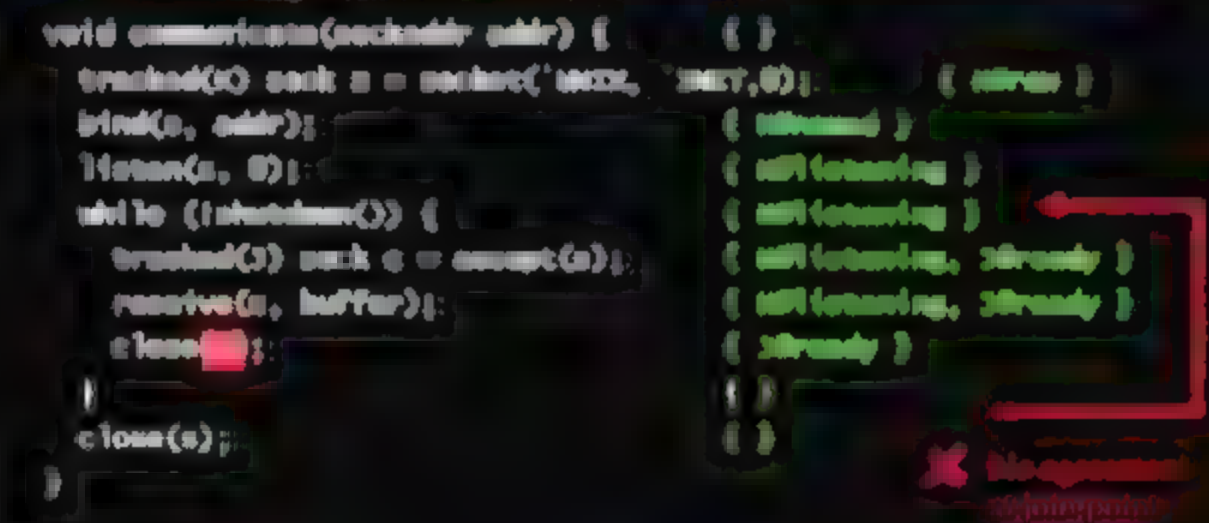
Checking Socket Client Code

Checking (Wrong) Socket Client Code

```
void communicate(sockaddr addr) {
  int s = socket(AF_INET, SOCK_DGRAM, 0);
  bind(s, addr);
  listen(s, 0);
  while (!shutdown()) {
    int c = accept(s);
    receive(s, buffer);
    close(c);
  }
  close(s);
}
```

Checking (Wrong) Socket Client Code

Checking (Wrong) Socket Client Code



Checking (Wrong) Socket Client Code

```
void communicate(sockaddr addr) {
  int s = socket(AF_INET, SOCK_STREAM, 0);
  bind(s, addr);
  listen(s, 0);
  while (!shutdown()) {
    int c = accept(s);
    receive(s, buffer);
    close(c);
  }
  close(s);
}
```

```
{ }
{ AF_INET }
{ SOCK_STREAM }
{ addr }
{ s, addr }
{ s, 0 }
{ s, 0 }
{ s, shutdown }
{ s, shutdown }
{ shutdown }
{ }
{ }
```

✗ Looking buy T

Checking (Wrong) Socket Client Code

Vault Research

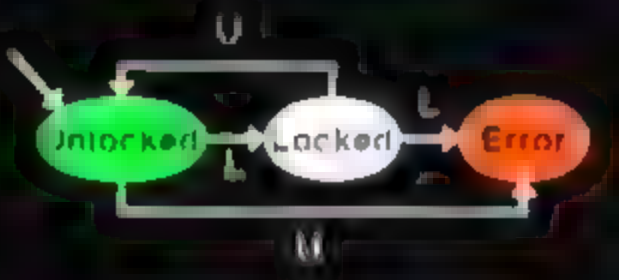
- Few new language features express and check many usage rules
  - Still imperative programming style
  - Handle "real" applications: device drivers, DirectX
  - Check "real" rules that developers commonly violate
- On-going research
  - Usage rules in C#
  - Safe, explicit memory management in CLR

SLAM (Tom Ball, Sriram Rajamani)

- Input
  - C source code, "as is"
  - API rules in SLIC language
- Automatically create abstraction of C program
  - Abstract model = Boolean program
- Systematic exploration of model's state space
  - Does feasible path through program lead to error state in SLIC?
- Demand-driven refinement of model
  - Exclude infeasible paths

API Rule for Locking

State Machine



API Rule for Locking

State Machine

SLIC

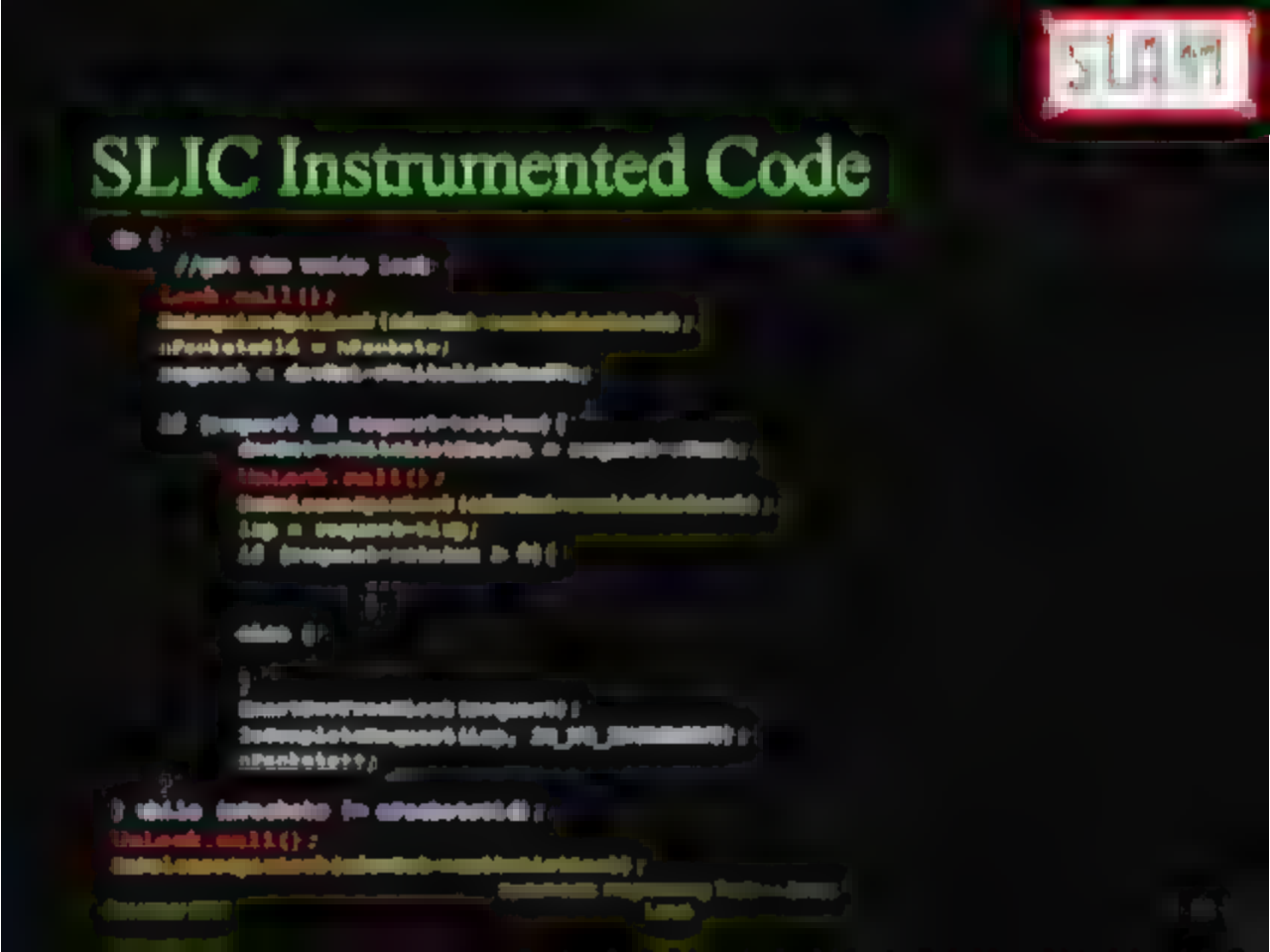
```
state {
  int locked = 0;
}

Lock.call {
  if (locked==1) abort;
  else locked = 1;
}

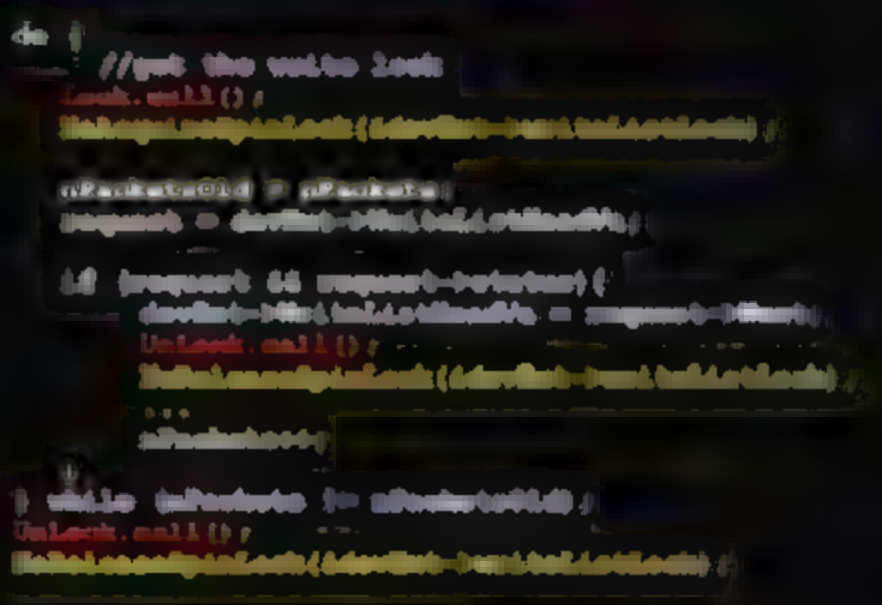
Unlock.call {
  if (locked==0) abort;
  else locked = 0;
}
```

Is Locking Protocol Respected?

SLIC Instrumented Code



State-based Search Fails



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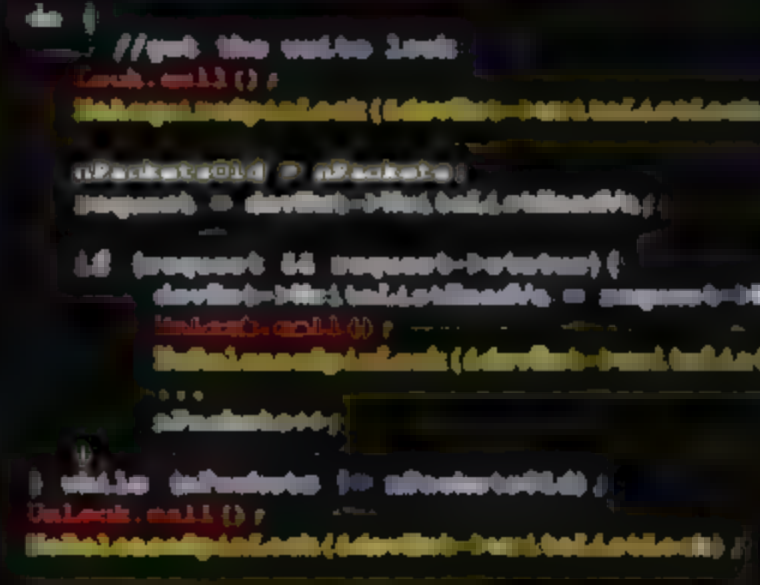

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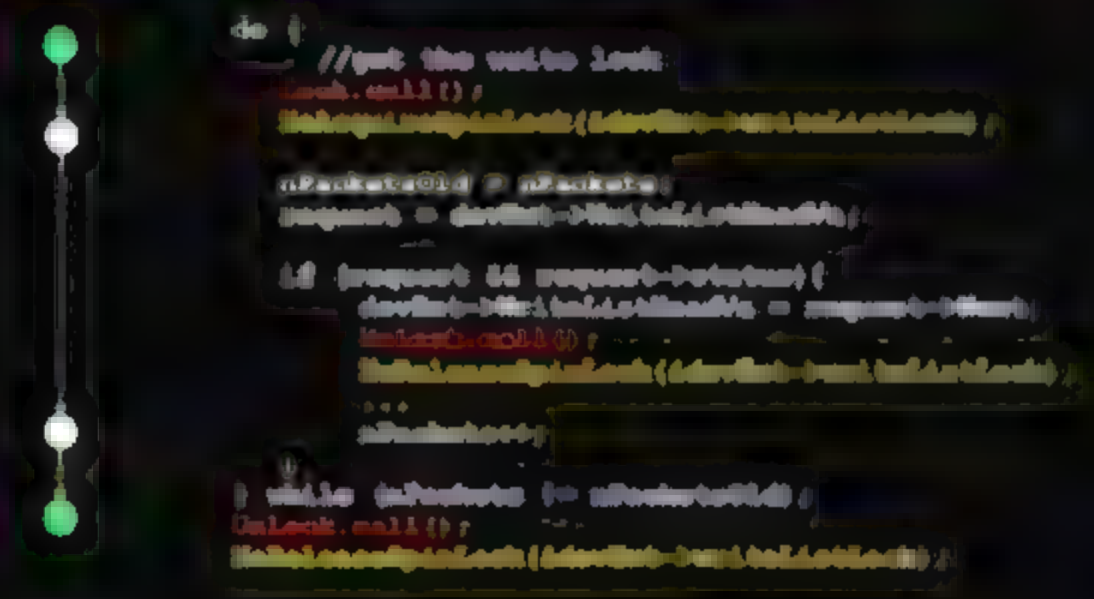

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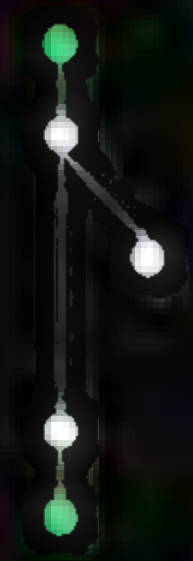
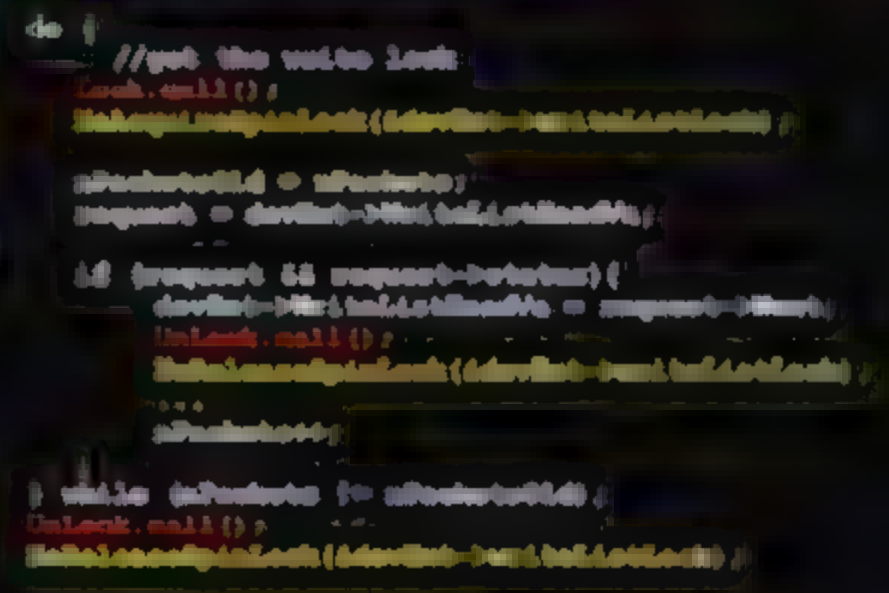




State-based Search Fails

```
do {
    //get the value level
    Level.val();
    [obj getObjectAtLevel:(level+1) withValue:&value];

    nPacketsOld = nPackets;
    request = [self findRequest:&value];

    if (request && request->active){
        [self.tableView beginUpdates];
        [tableView deleteRowsAtIndexPaths:
        ...
        [tableView endUpdates];
    }
} while (nPackets != nPacketsOld);
[level.val();
[obj getObjectAtLevel:(level+1) withValue:&value];
```

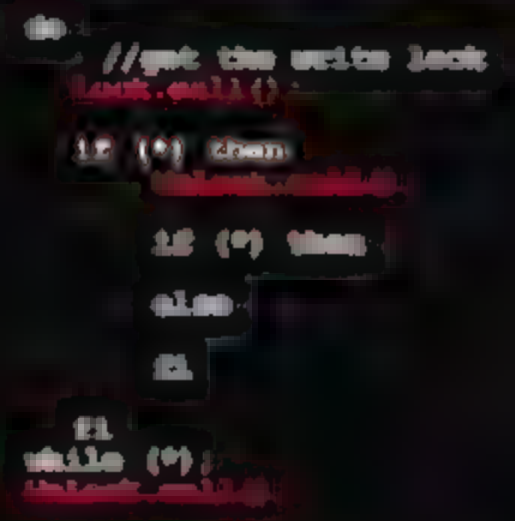
State-based Search Fails

```
do {
    //get the write lock
    lock.wait();
    ...
    nPacketsOld = pPackets;
    request = devMgr->findLowPriorityReq();
    ...
    if (request && request->active) {
        devMgr->freeLowPriorityReq = request->next;
        Unlock.call();
        ...
        nPacketsOld++;
    }
} while (nPackets != nPacketsOld);
Unlock.call();
```

State-based Search Fails

```
do {
    //get the write lock
    lock.wait();
    ...
    if (request && request->active) {
        ...
        unlock.wait();
        ...
    }
} while (...);
unlock.wait();
```

Boolean Program; Abstraction 1



Boolean Program; Abstraction 1

```
do
    //get the write lock
    lock.call();
    if (*) then
        unlock.call();
        if (*) then
        else
        fi
    fi
od;
while (*);
```

Boolean Program; Abstraction 1

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    //get the write lock
    lock.call();
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        else
        fi
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od
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Boolean Program; Abstraction 1

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do {
    //get the write lock
    lock.call();
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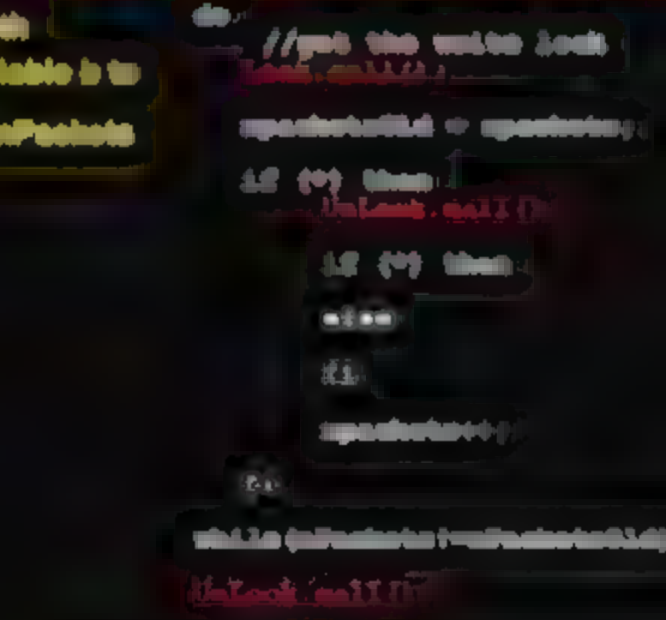
        fi
    fi
} while (*);
```

Boolean Program; Refine Abstraction

- Examine infeasible path
- Introduce boolean variable b to represent:
  nPacketsOld == nPackets



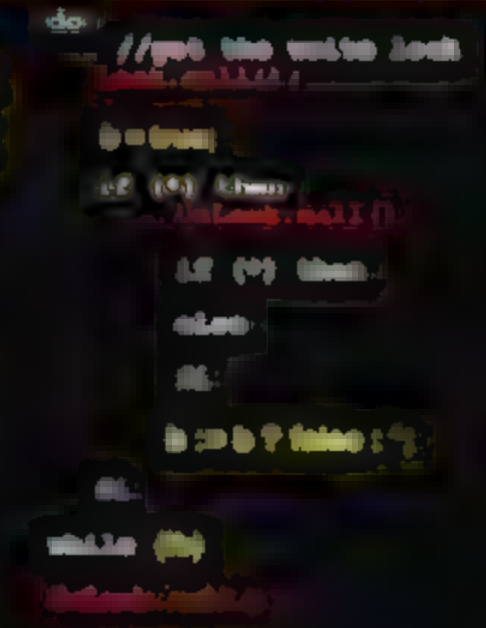
Boolean Program; Refine Abstraction

- [illegible infeasible path]
- [introduces boolean variable b to represent:
  nPacketsOld == nPackets]

```
do
  //get the write lock
  KeAcquireSpinLock(...);
  nPacketsOld = nPackets;
  if (*) then
    IoReleaseCancelSpinLock(...);
    if (*) then
    else
    fi;
    nPackets++;
  fi;
while (nPacketsOld != nPackets);
IoReleaseCancelSpinLock(...);
```

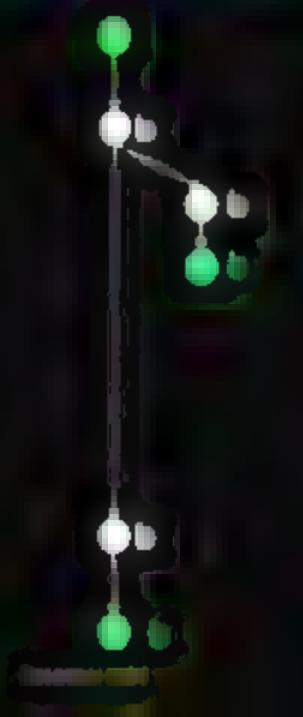
Boolean Program; Refine Abstraction

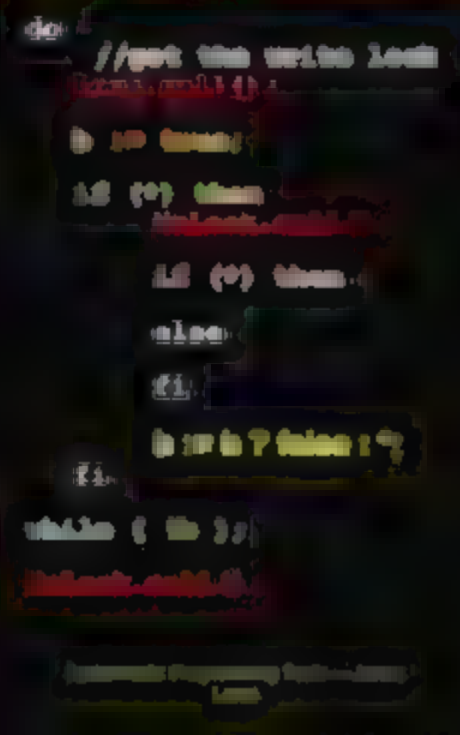
- Learning infeasible path
- Introduce boolean variable b to represent:
  nPacketsOld == nPackets



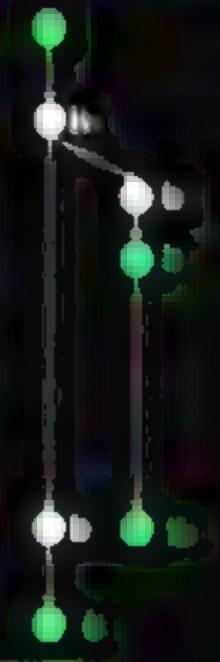
Boolean Program; Abstraction 2

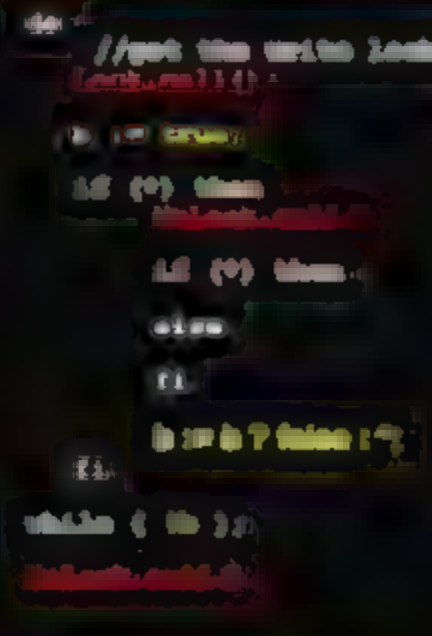
Boolean Program; Abstraction 2



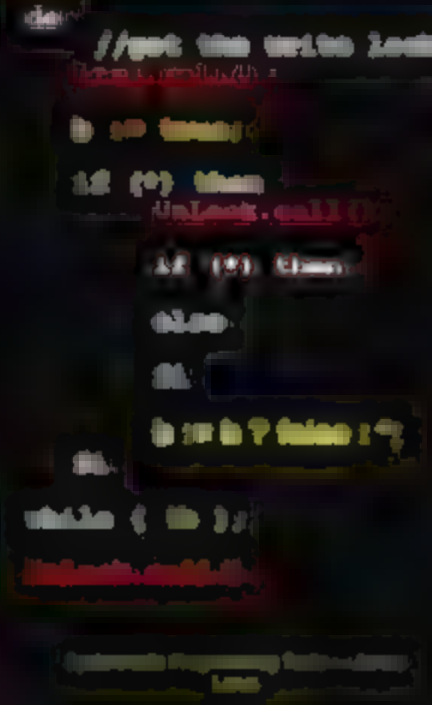


Boolean Program; Abstraction 2

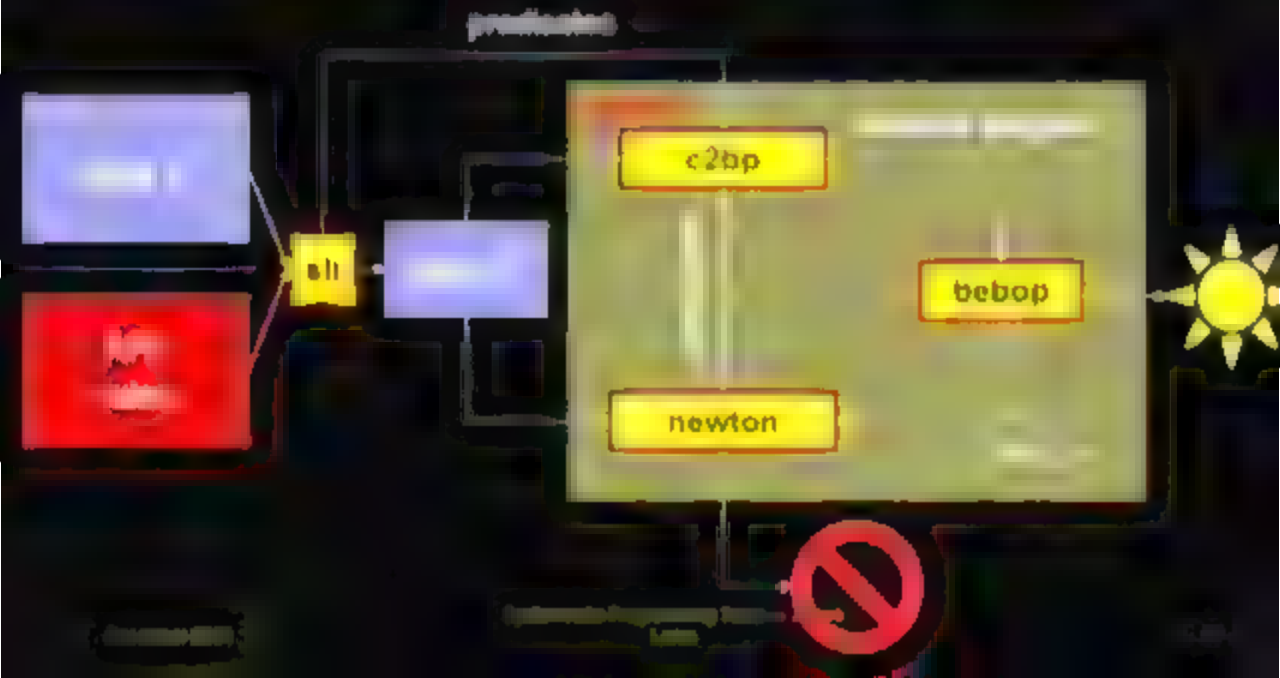




Boolean Program; Abstraction 2



Checking API Rules with SLAM



SLAM Summary

- Automatic analysis (no code annotation)
  - SLIC specification of API rules
- Report errors with source-level paths
- Very precise analysis
  - Minimize false positives
- Current research
  - Applying to device drivers
  - Tool scalability

The Static Driver Verifier

Thomas Ball
Sriram K. Rajamani

Software Productivity Tools

Programmer Productivity
Research Center

The Static Driver Verifier

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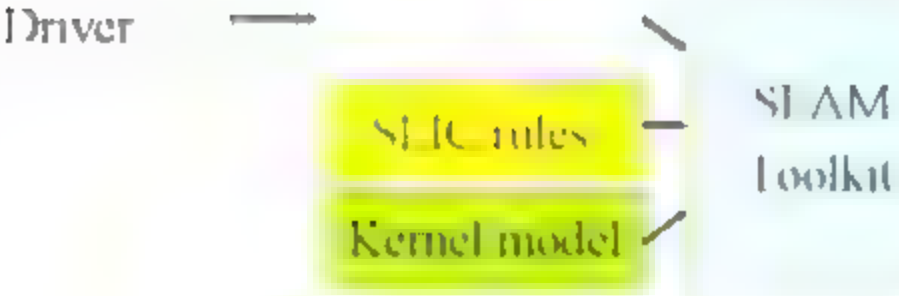
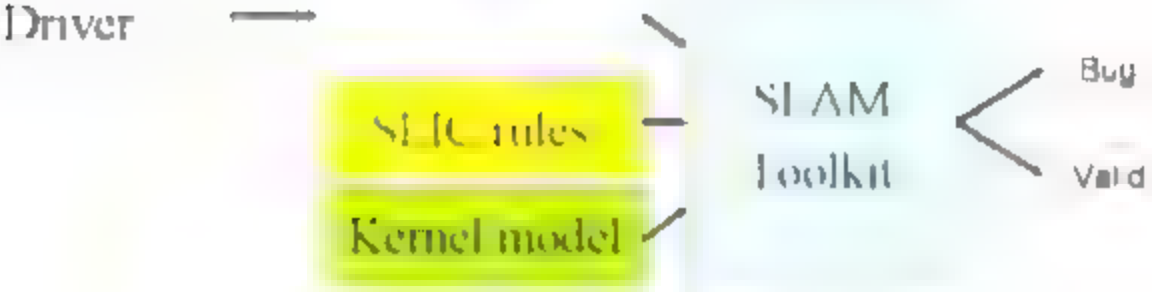
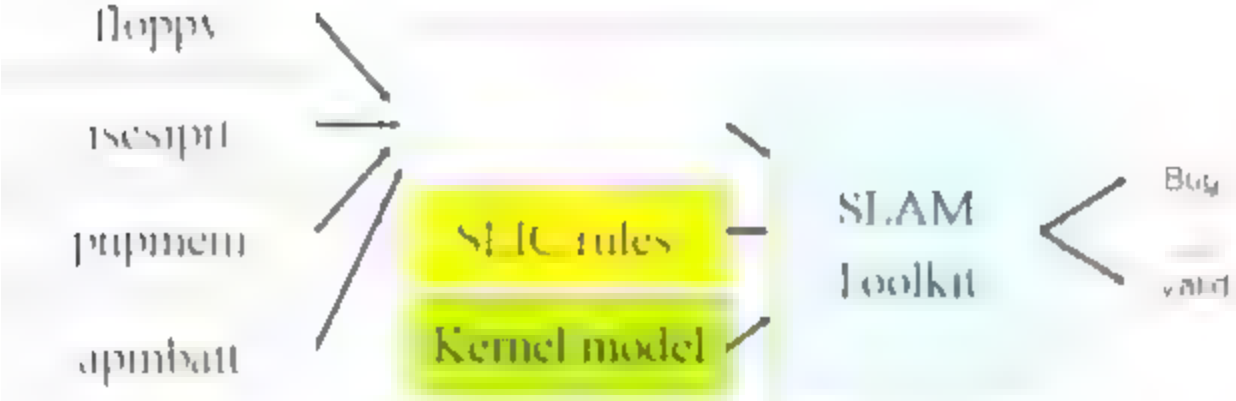
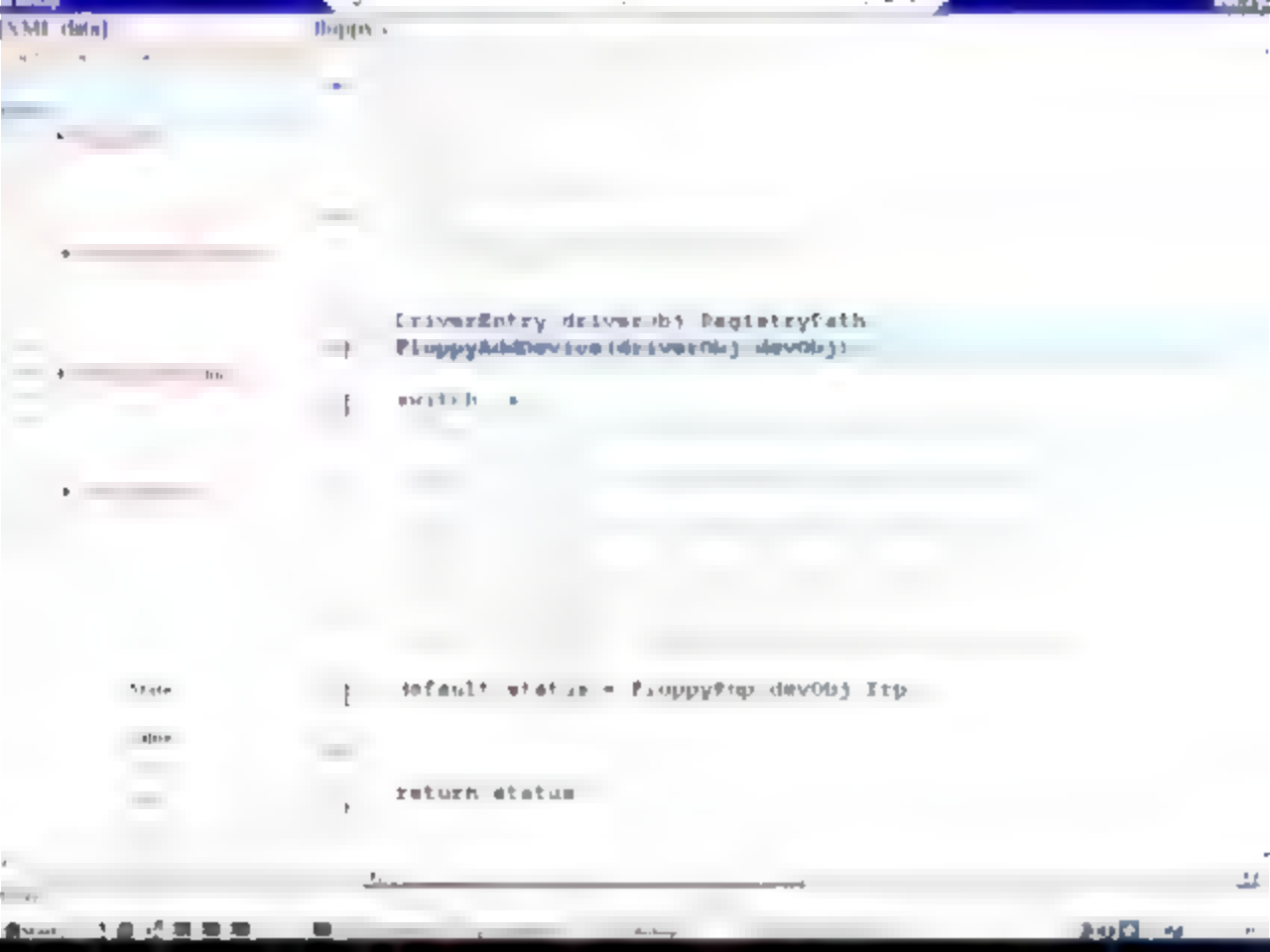


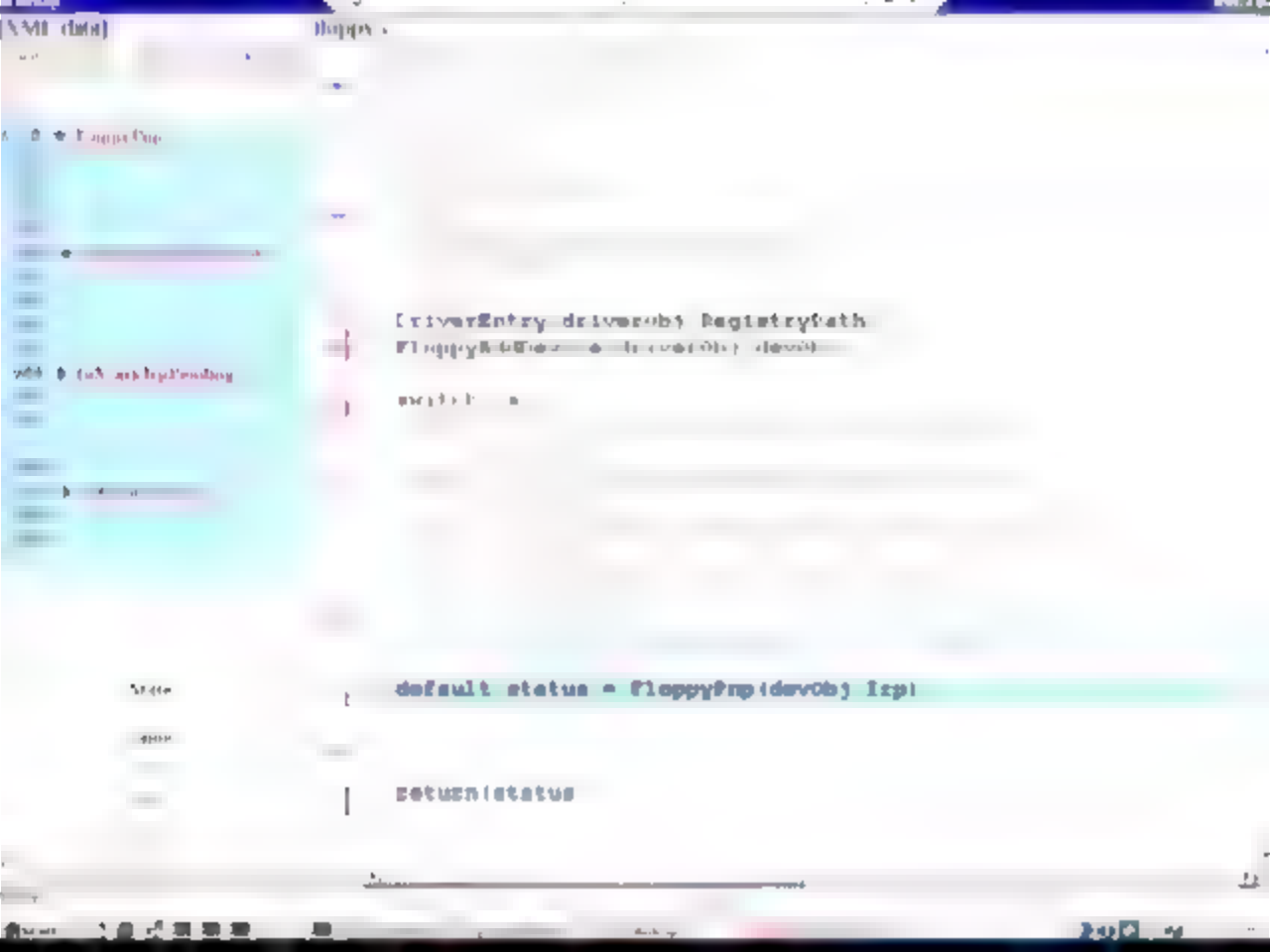
Static Driver Verifier

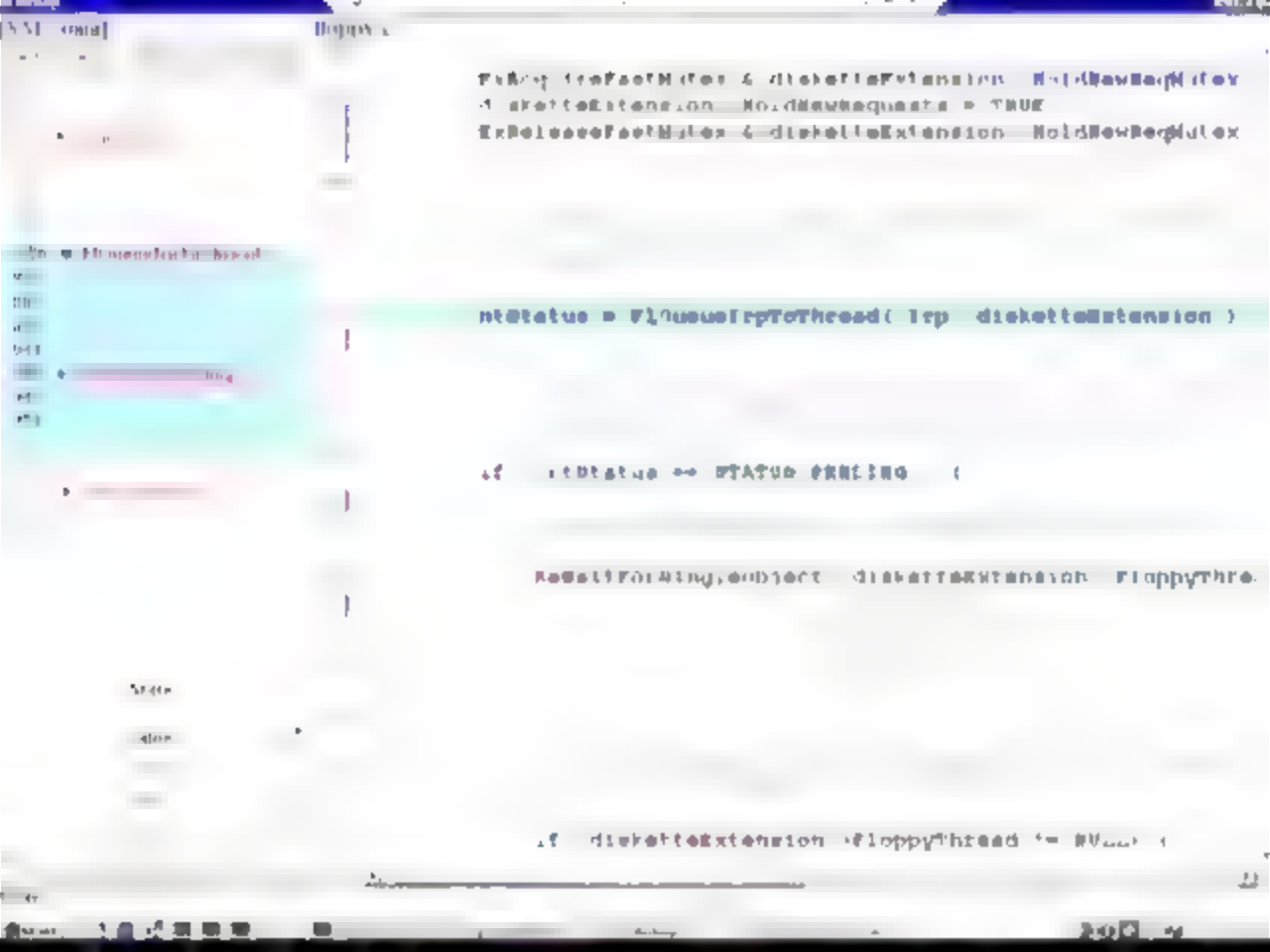


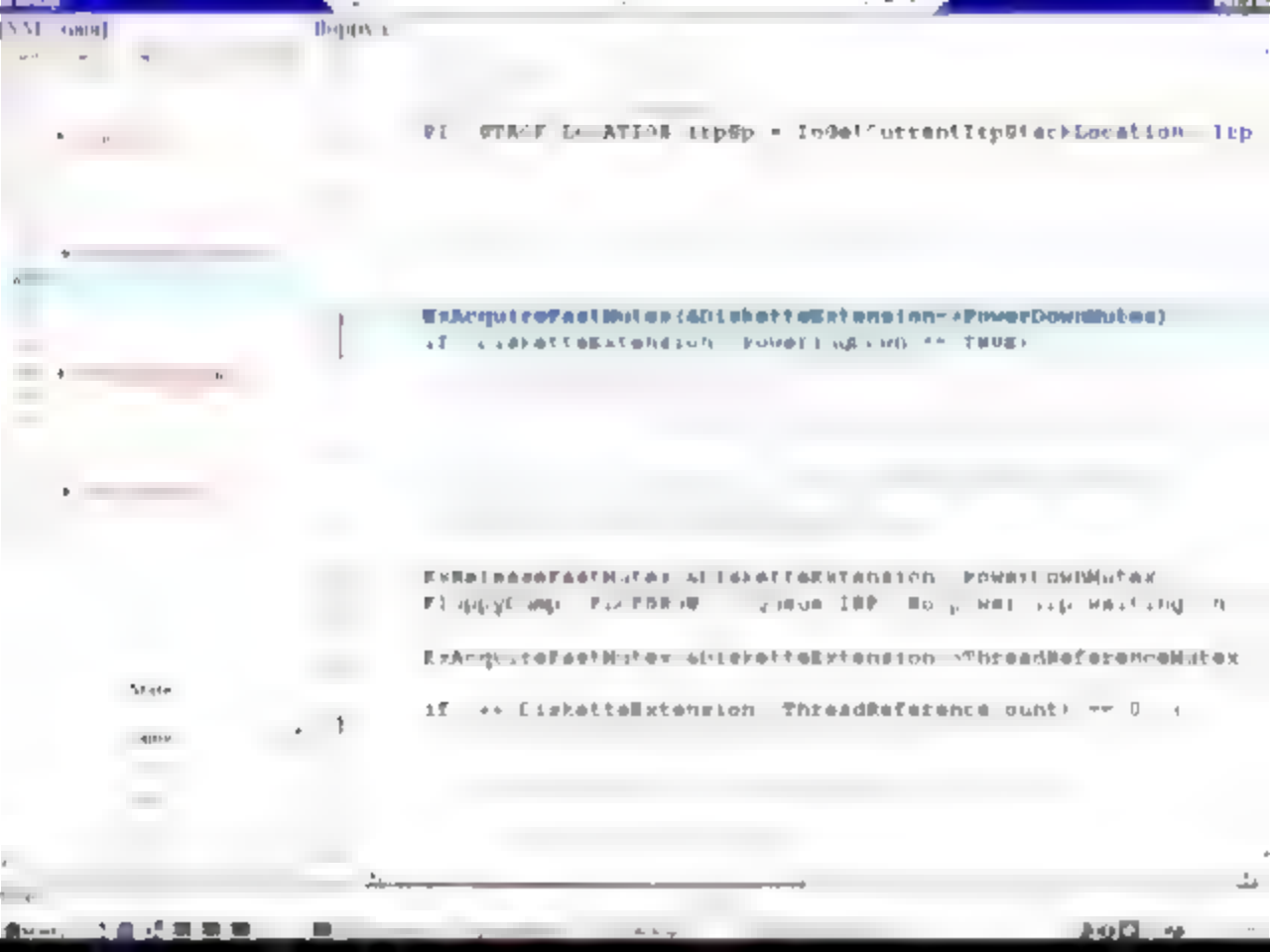
Static Driver Verifier (ii)

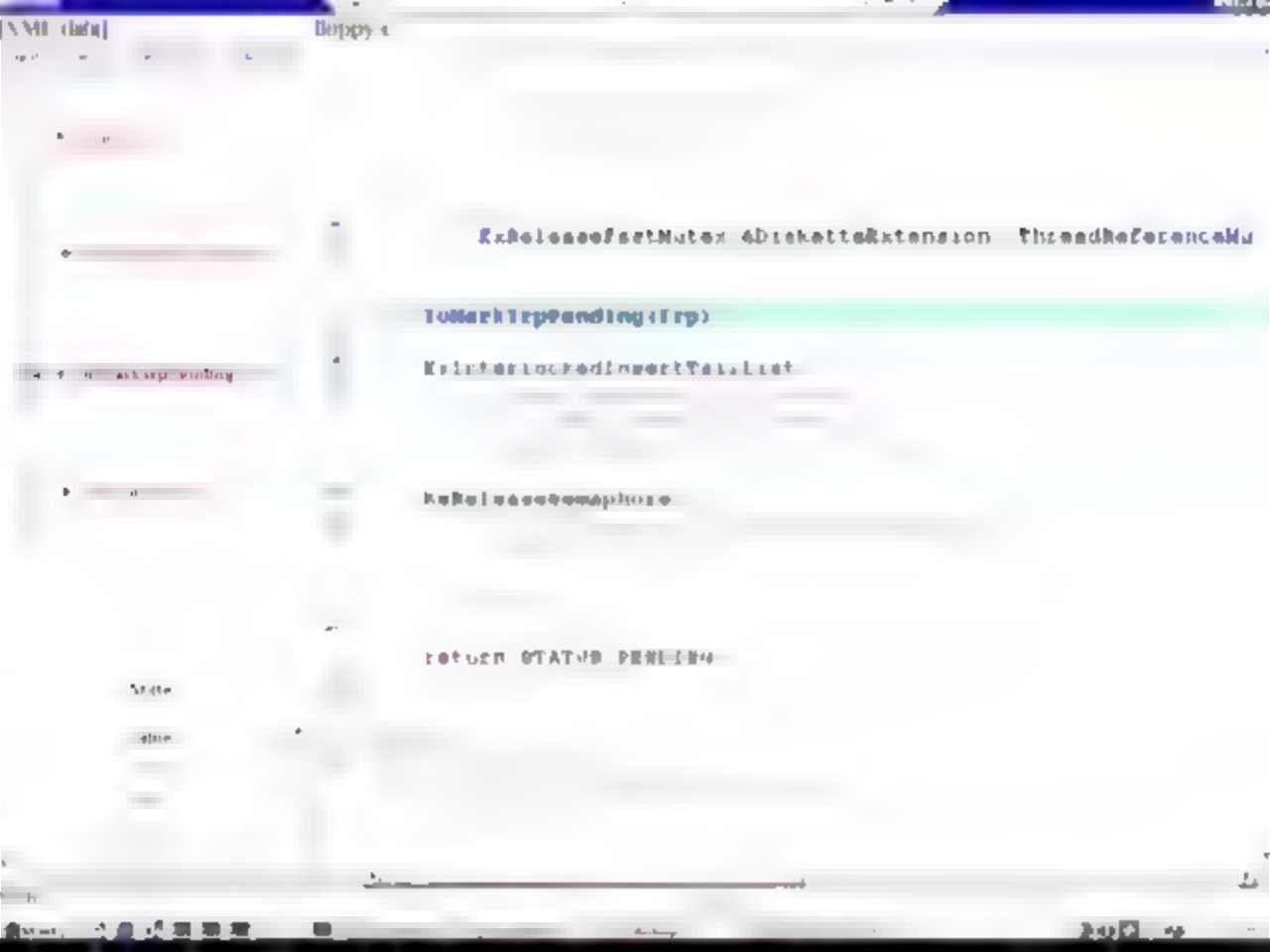


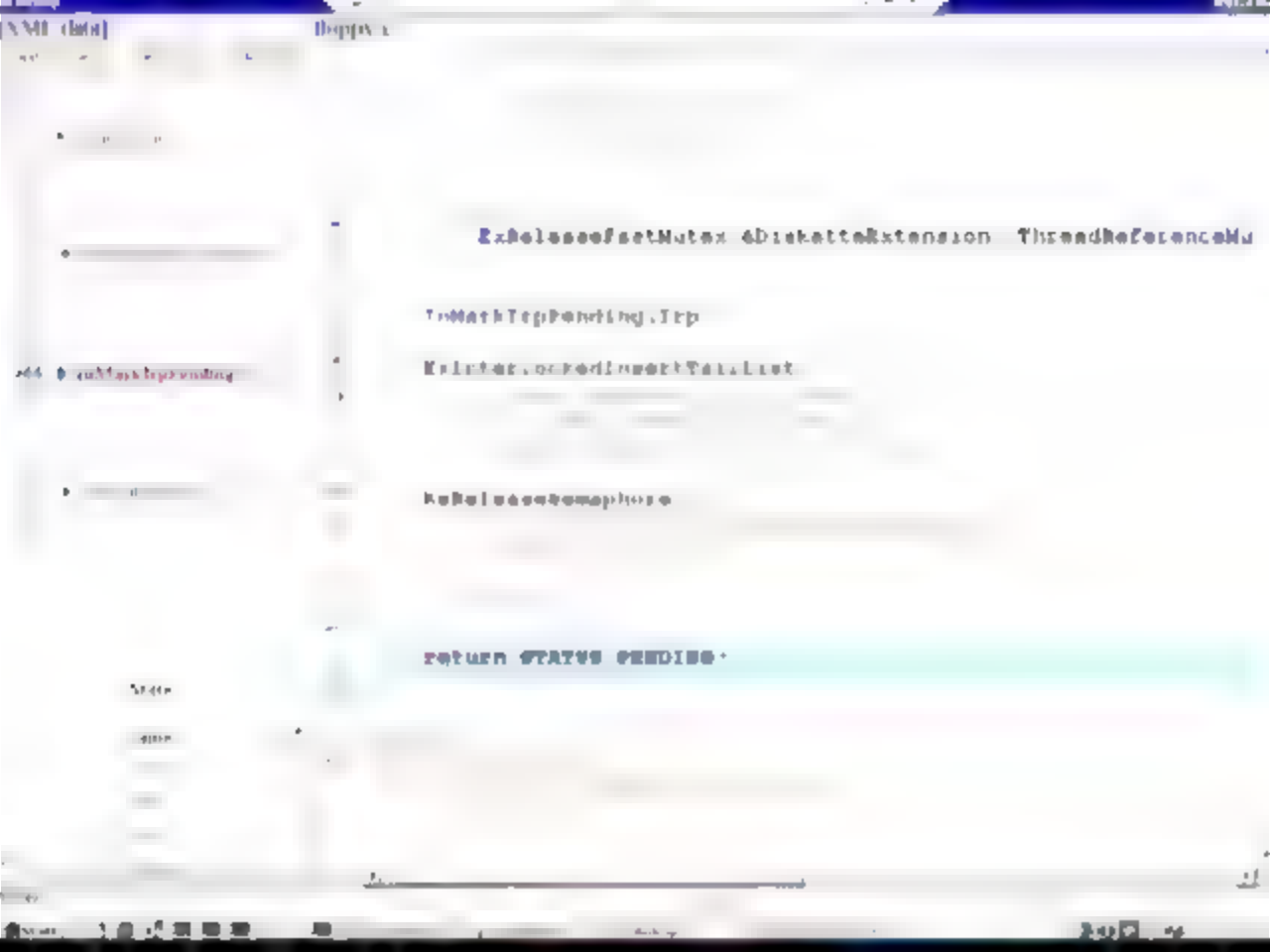


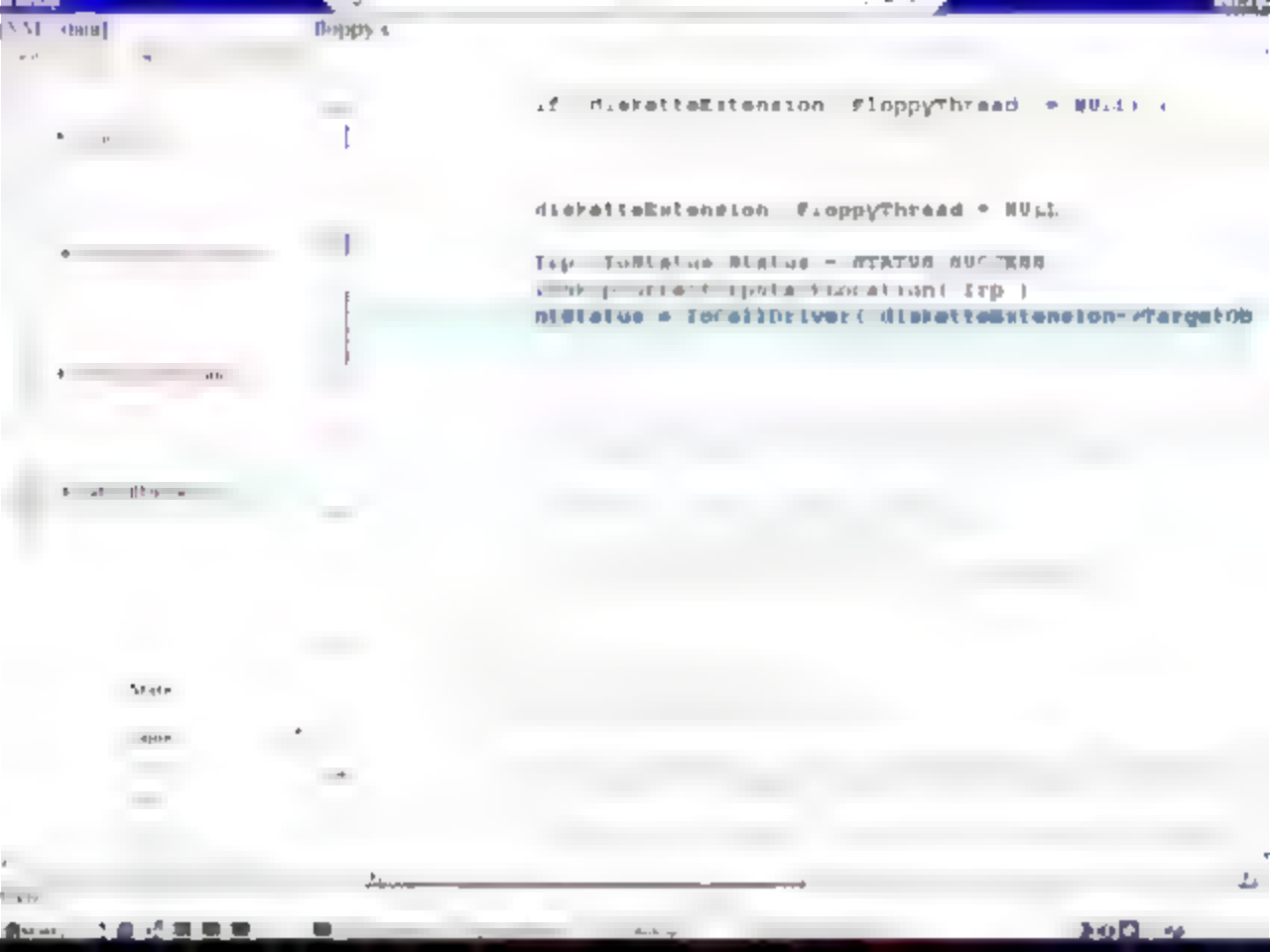


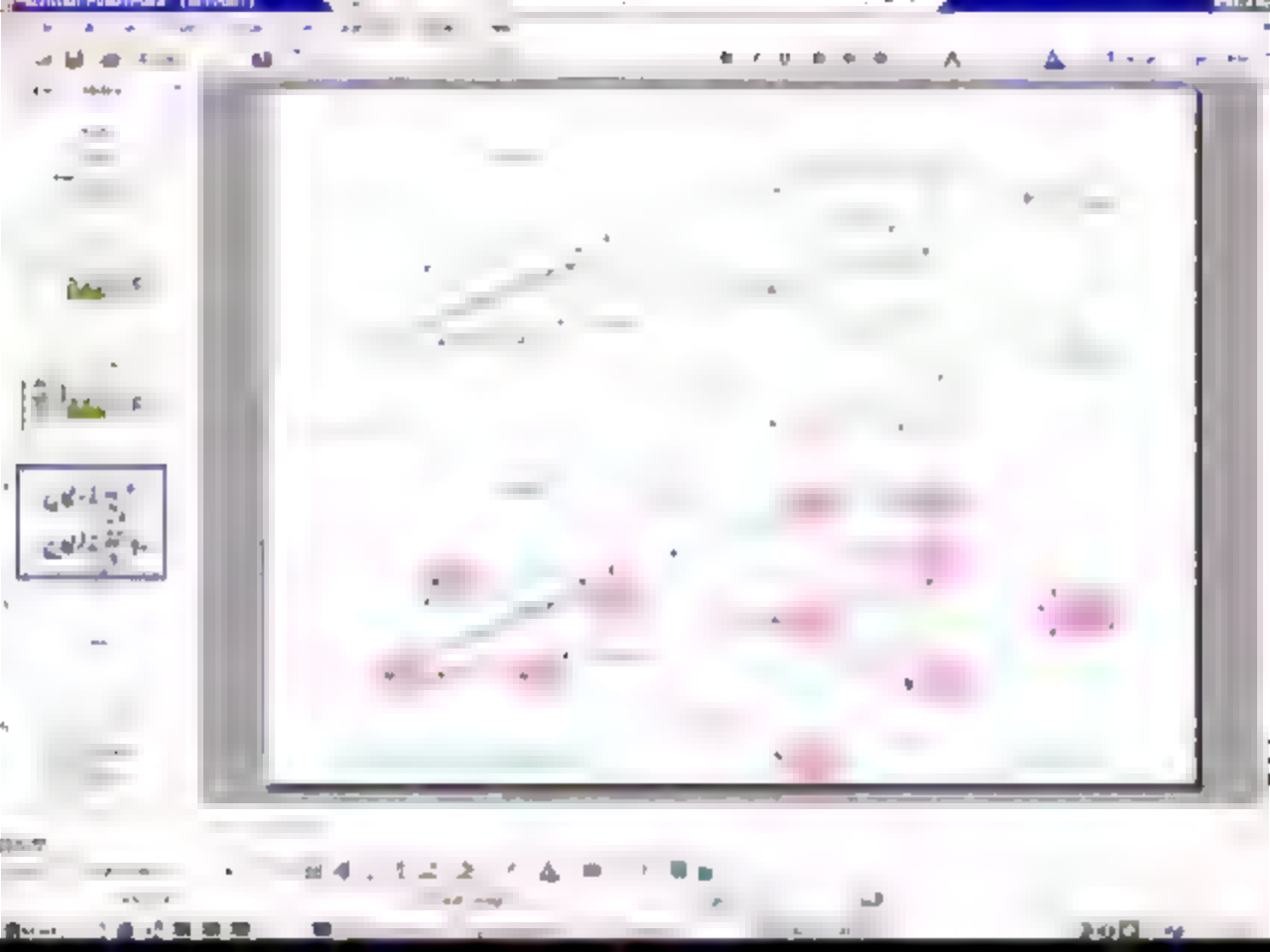


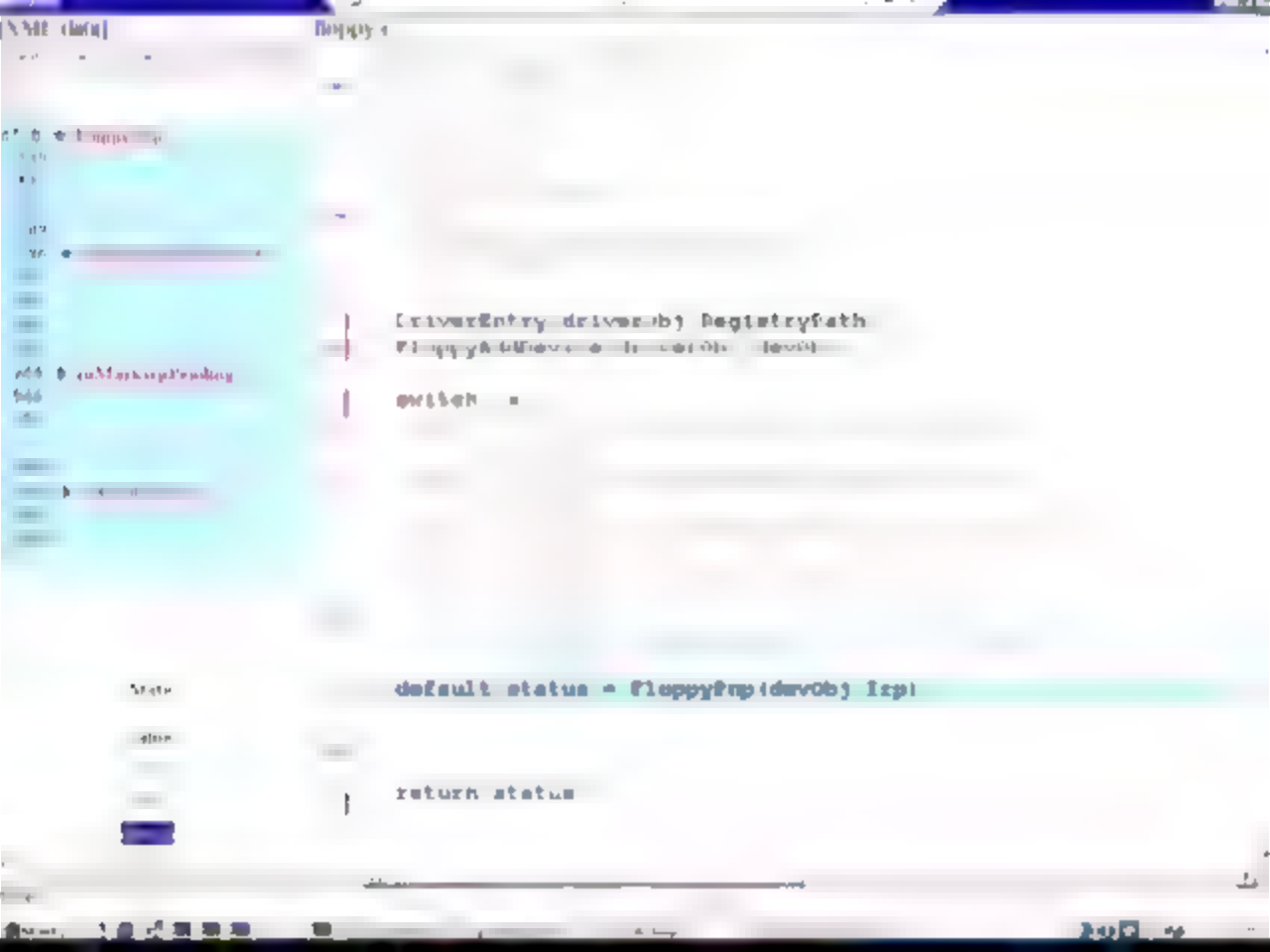










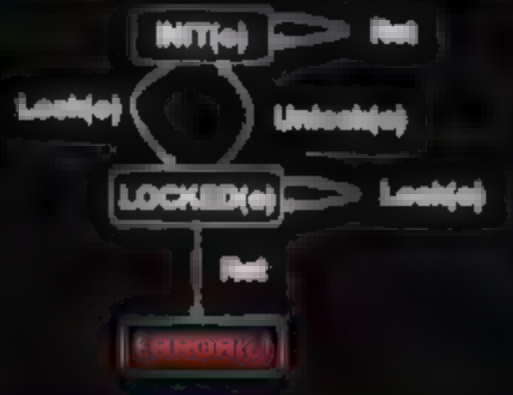


ESP (Manuvir Das)

- Error detection via scalable program analysis
- Similar to SLAM:
  - SLIC-like specification
  - Automatic analysis
  - Sound (finds all errors)
- Differences from SLAM:
  - Targeted at large (million+ LOC) C++ code bases
  - Only parameterized finite state protocols
  - Weaker (less precise) analysis

Parameterized Protocols

- FSM attached to data items
- Syntactic patterns trigger transitions



C++ code pattern	Transition
o->m_spinlock.Get()	Lock(o)
o->m_spinlock.Release()	Unlock(o)
return o	Ret

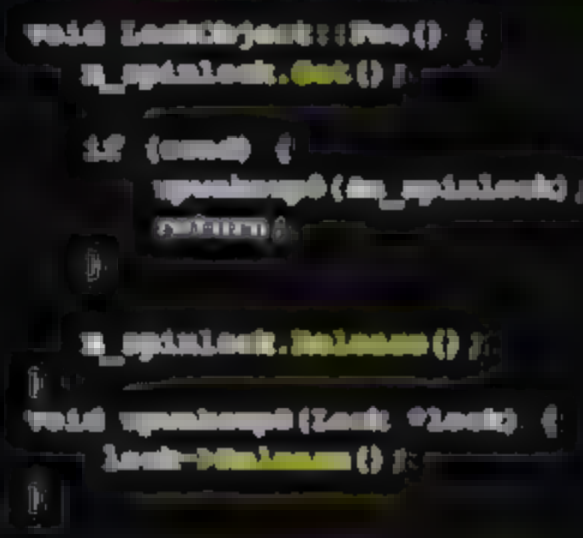
ESP Insight

- Three distinct entities
  - Sequence of actions along control flow path
  - Data involved in actions
    - o->Get(); p = o; p->Release();
  - Data involved in path feasibility
    - if (c) o->Get(); ... if (c) o->Release();
- Insight: use different static analyses to track each entity

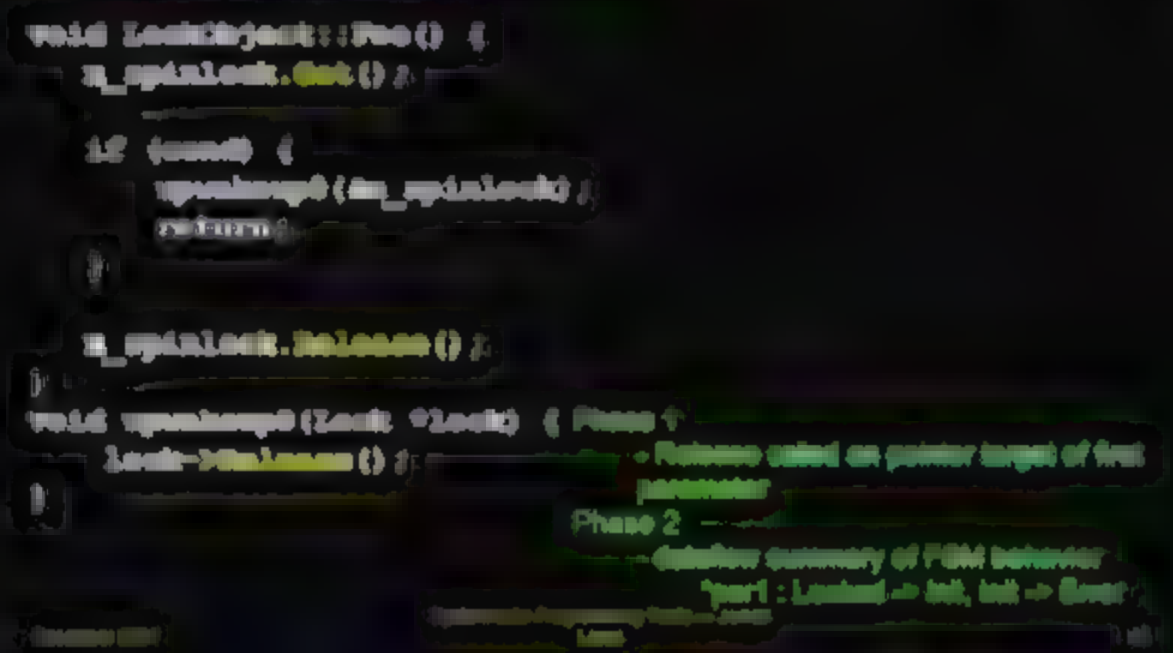
Three Phases of Static Analysis

1. Global value flow analysis
   - Use GOLF to build call and value flow graph
2. Global protocol tracking
   - Use dataflow and value flow to track protocols associated with data items
3. Local feasibility analysis
   - Use local abstract simulation + summaries from Phase II to rule out infeasible paths

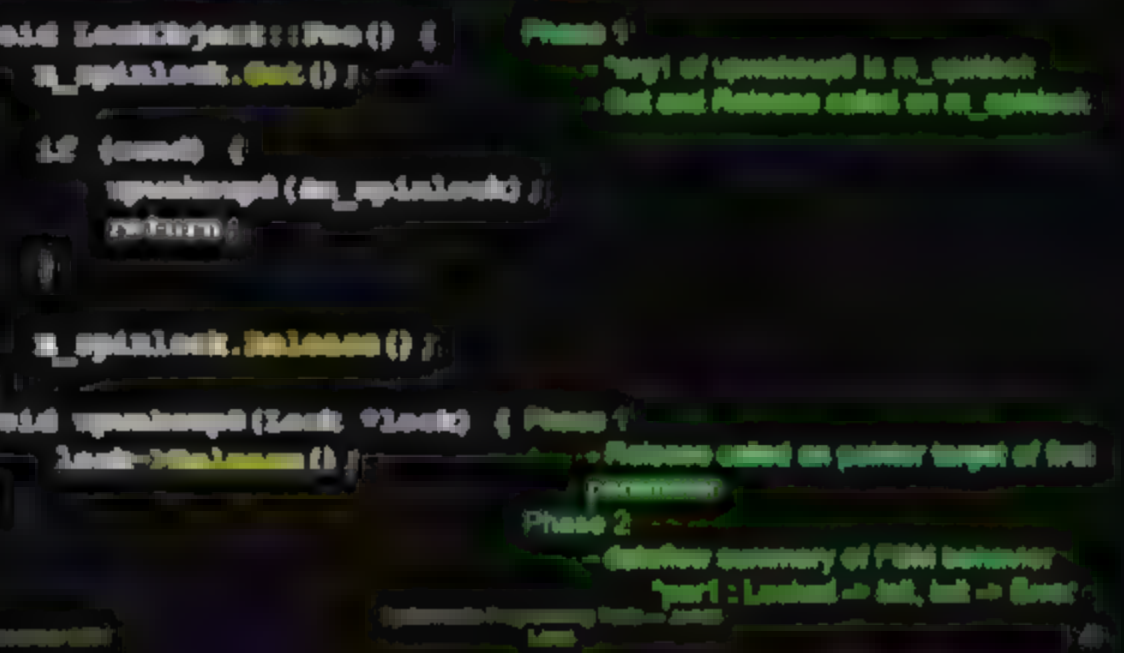
Example From SQL



Example From SQL

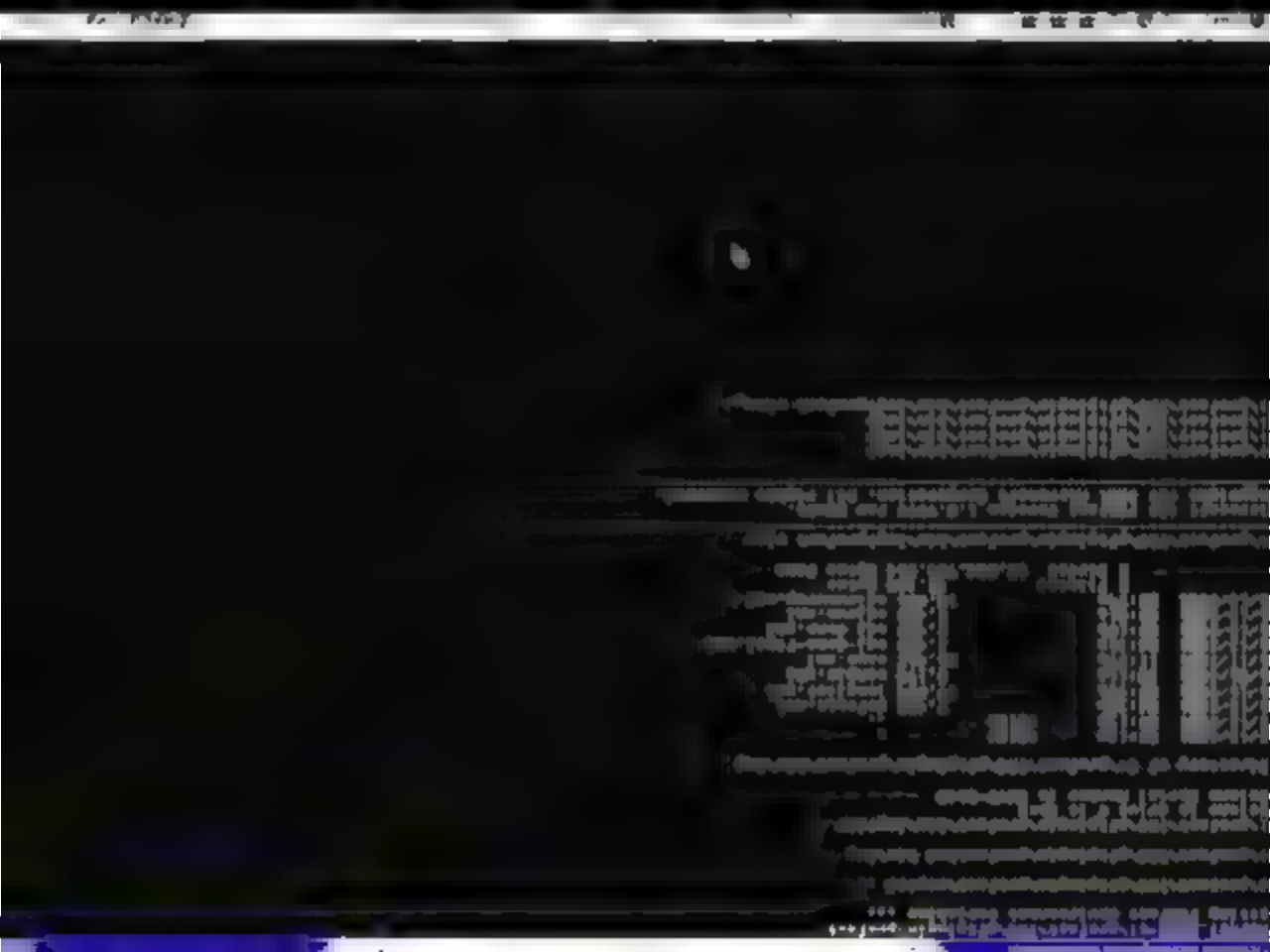


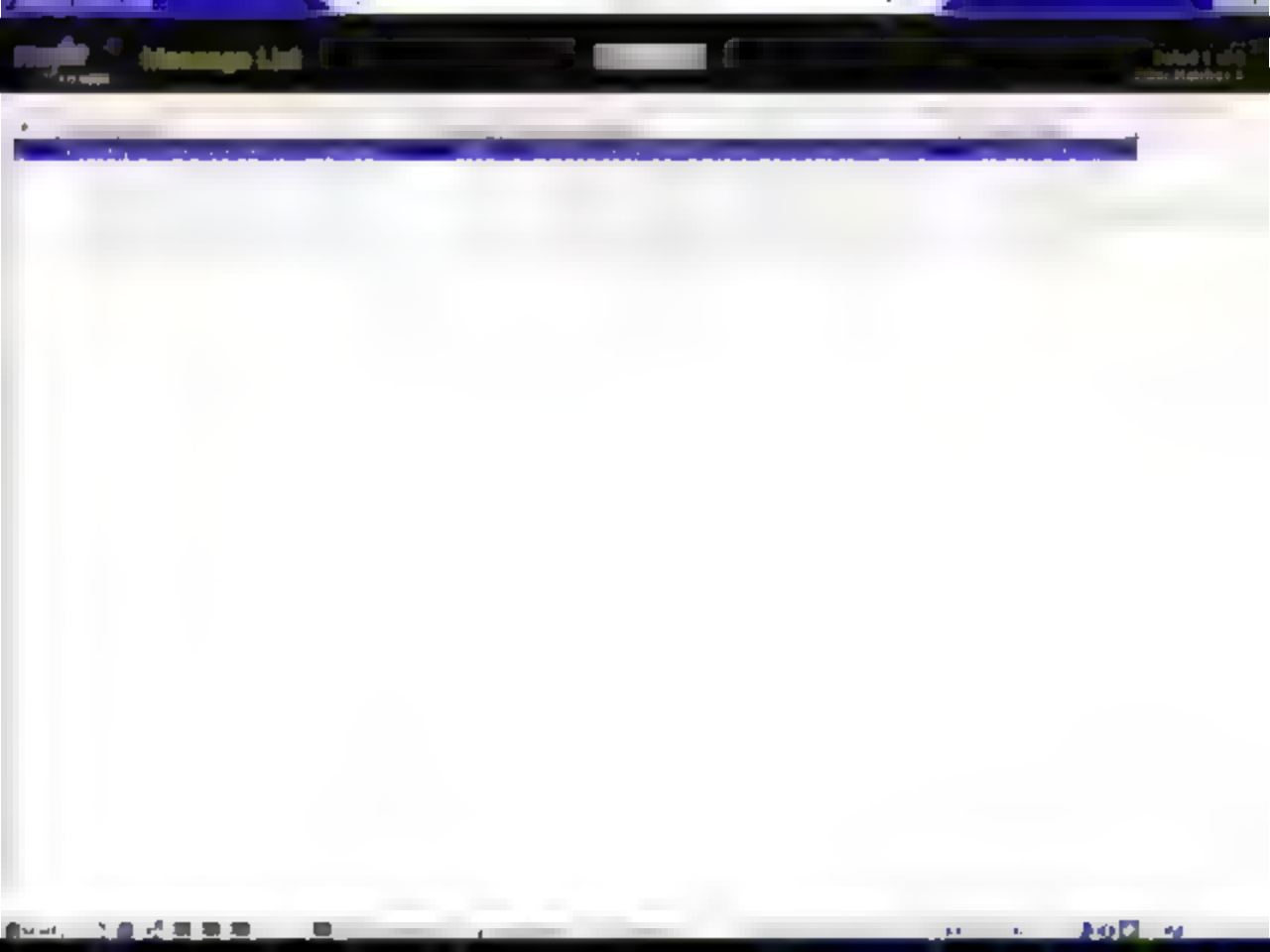
Example From SQL

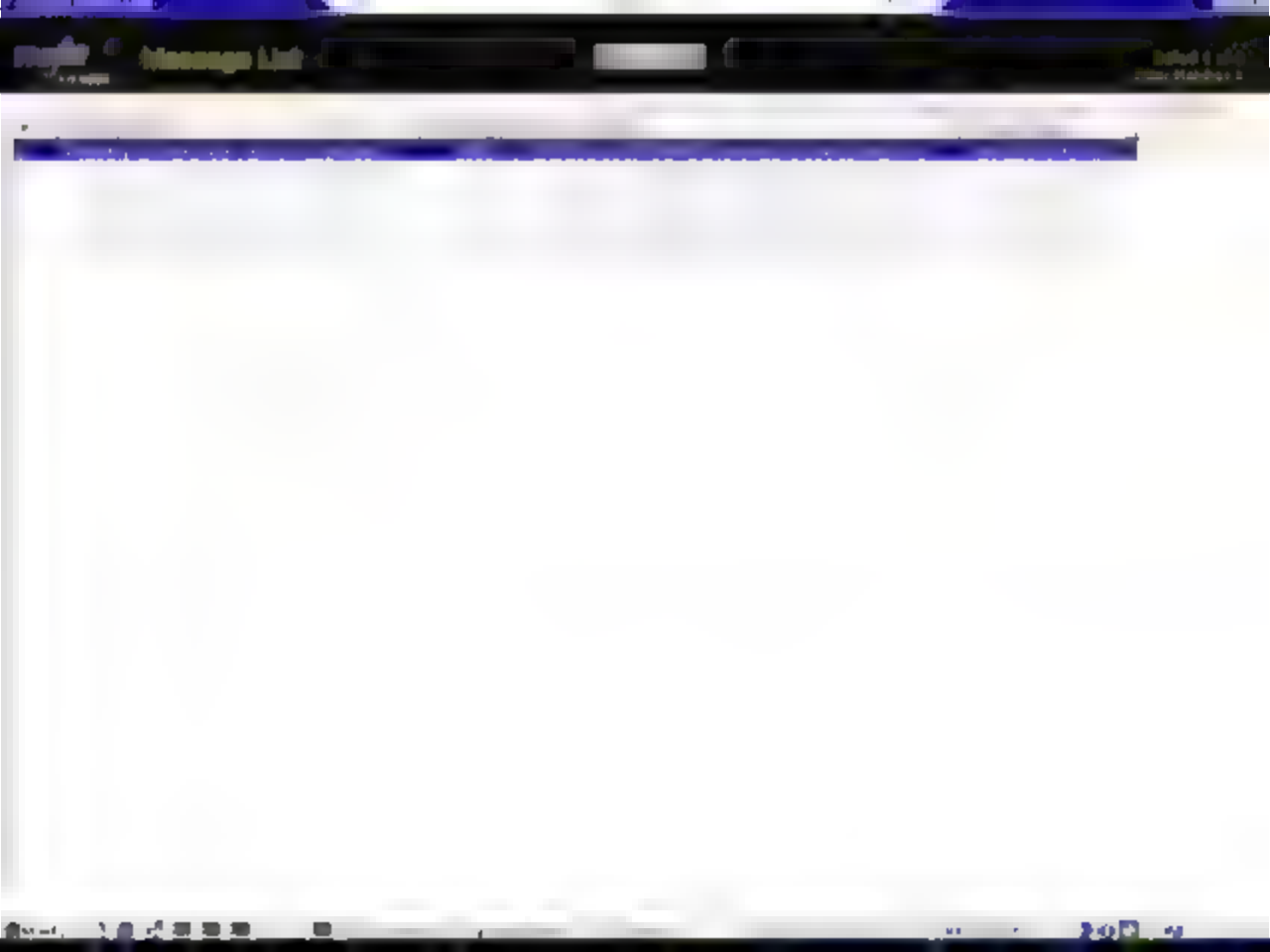


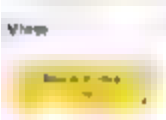
ESP Summary

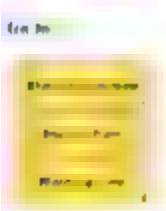
- Early implementation for C
  - Verified stdio usage (15 files) in 150K LOC program
- Extend to full C++ and improve speed
- Hypothesis
  - For many (protocols) errors, scalable analysis is sufficiently precise
  - Intricate usage patterns are difficult for programmers, as well as tools



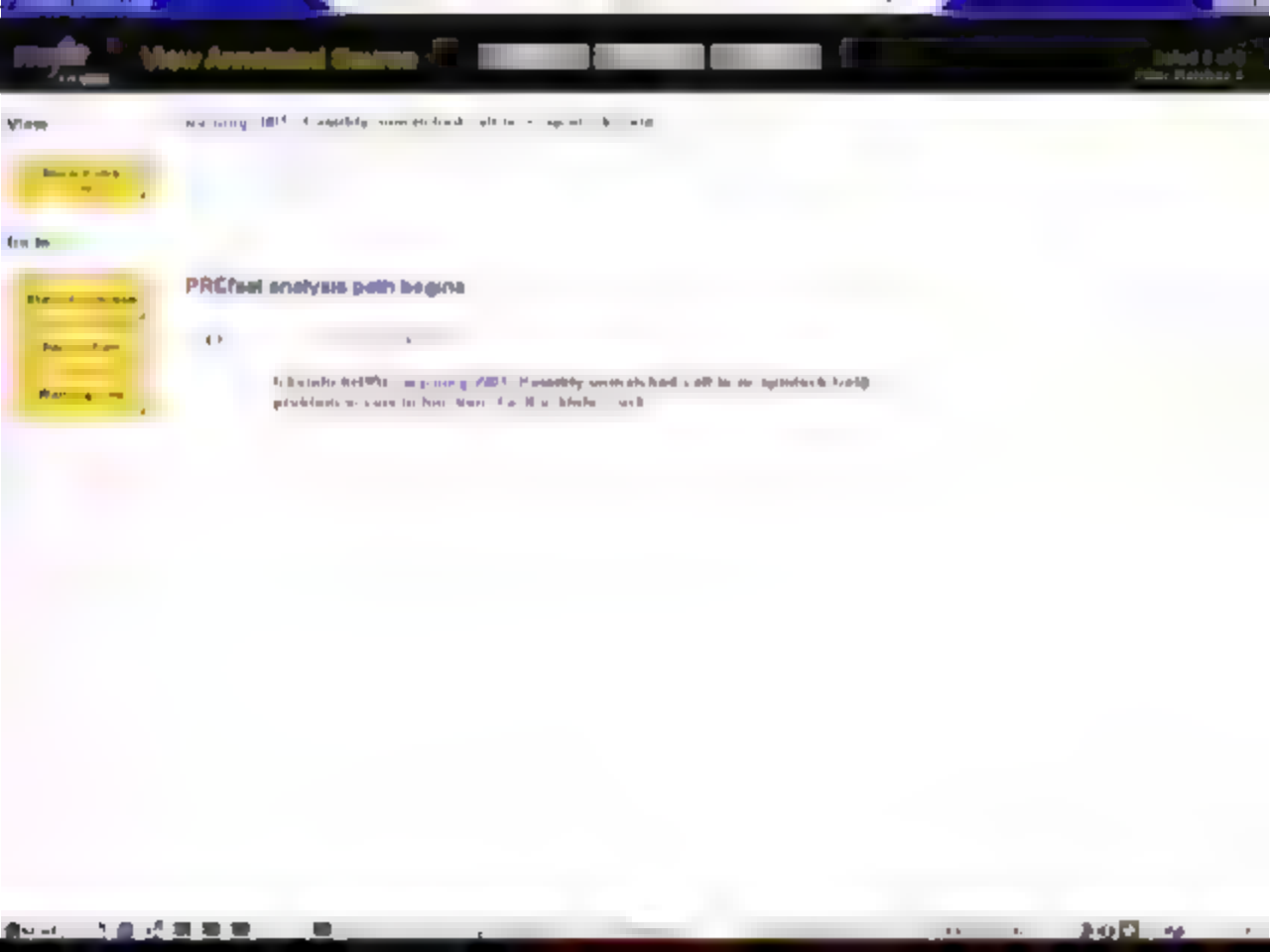


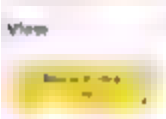


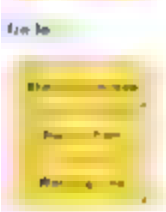




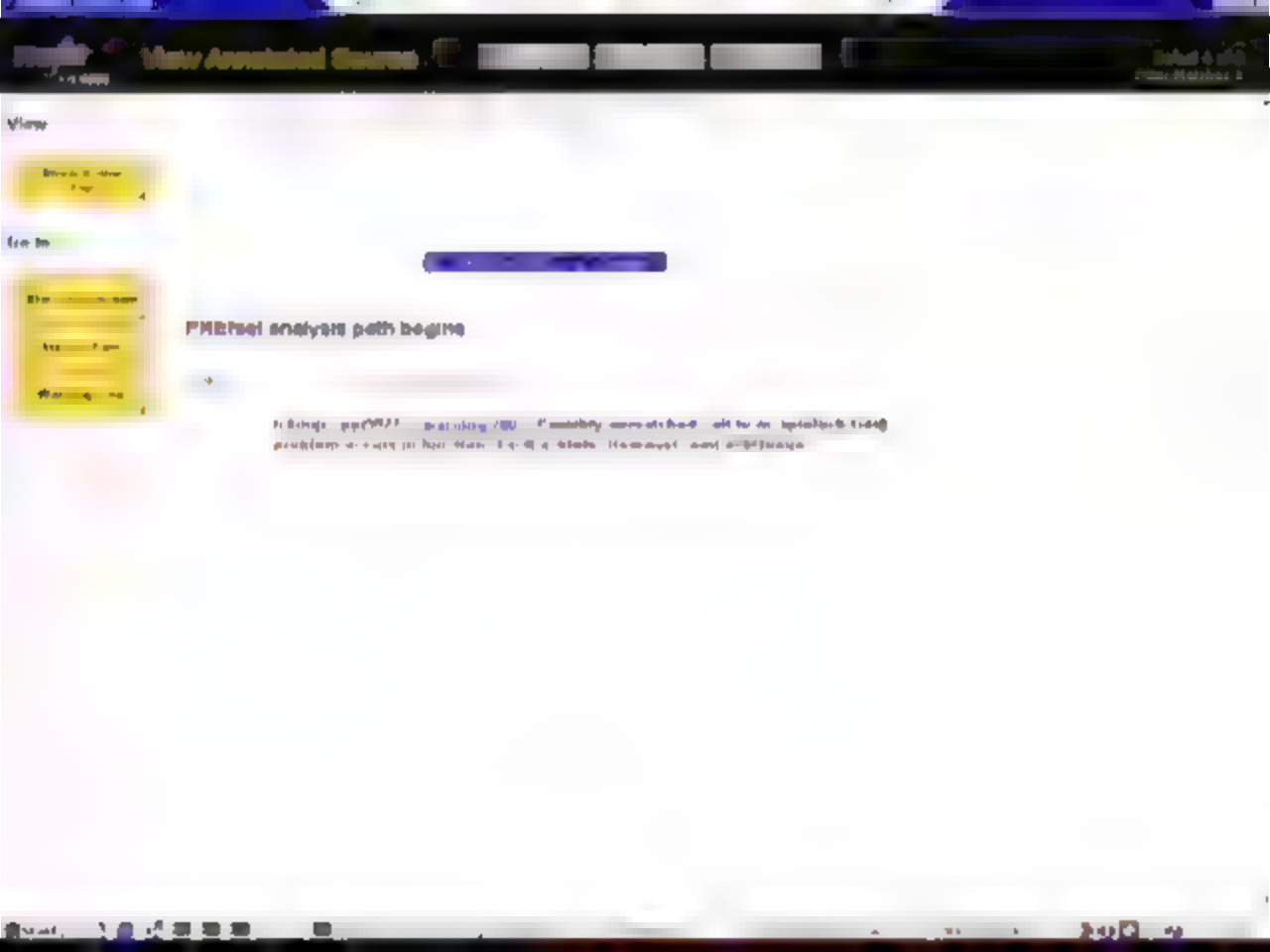
PAHfast analysis path begins

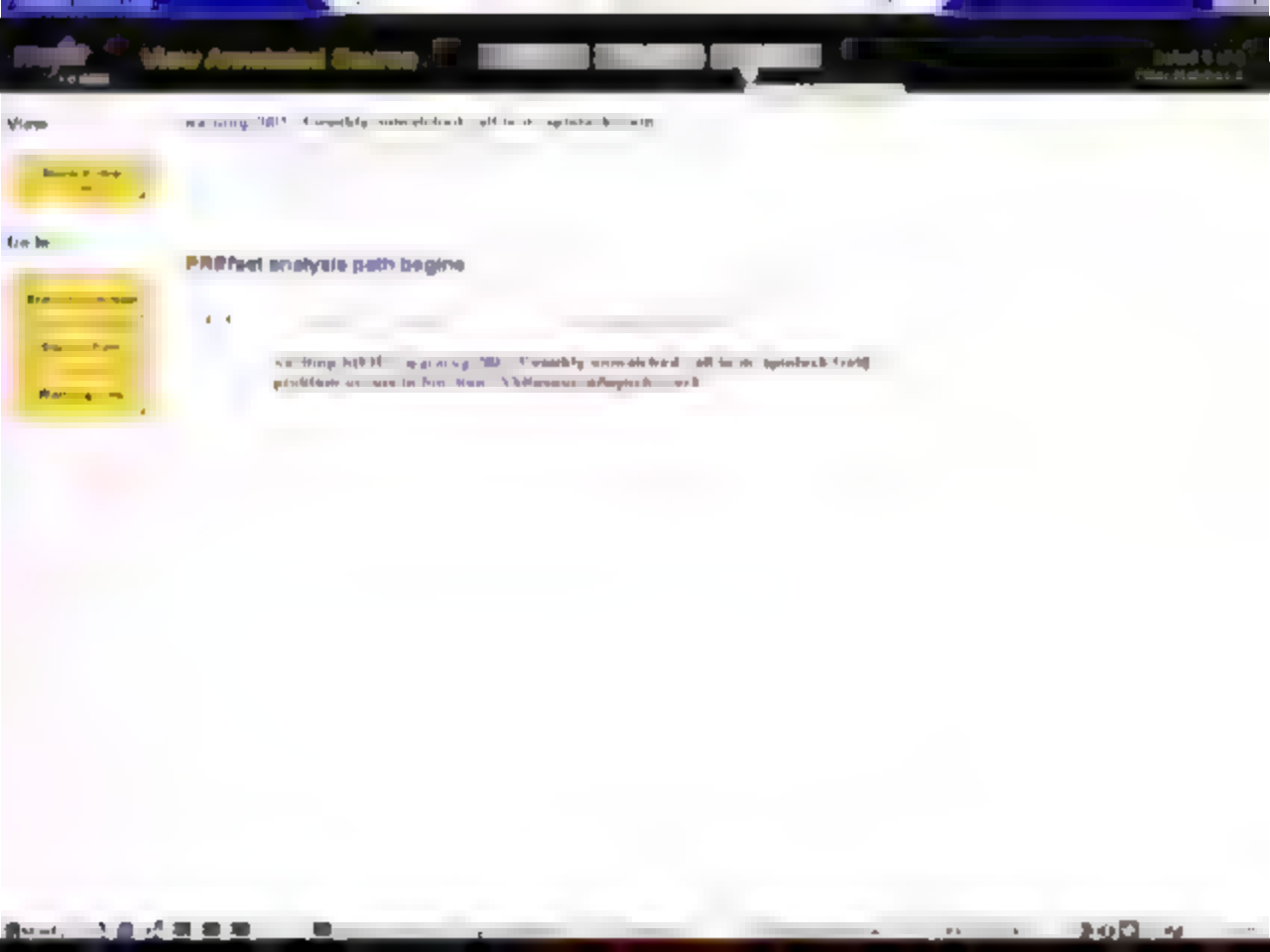


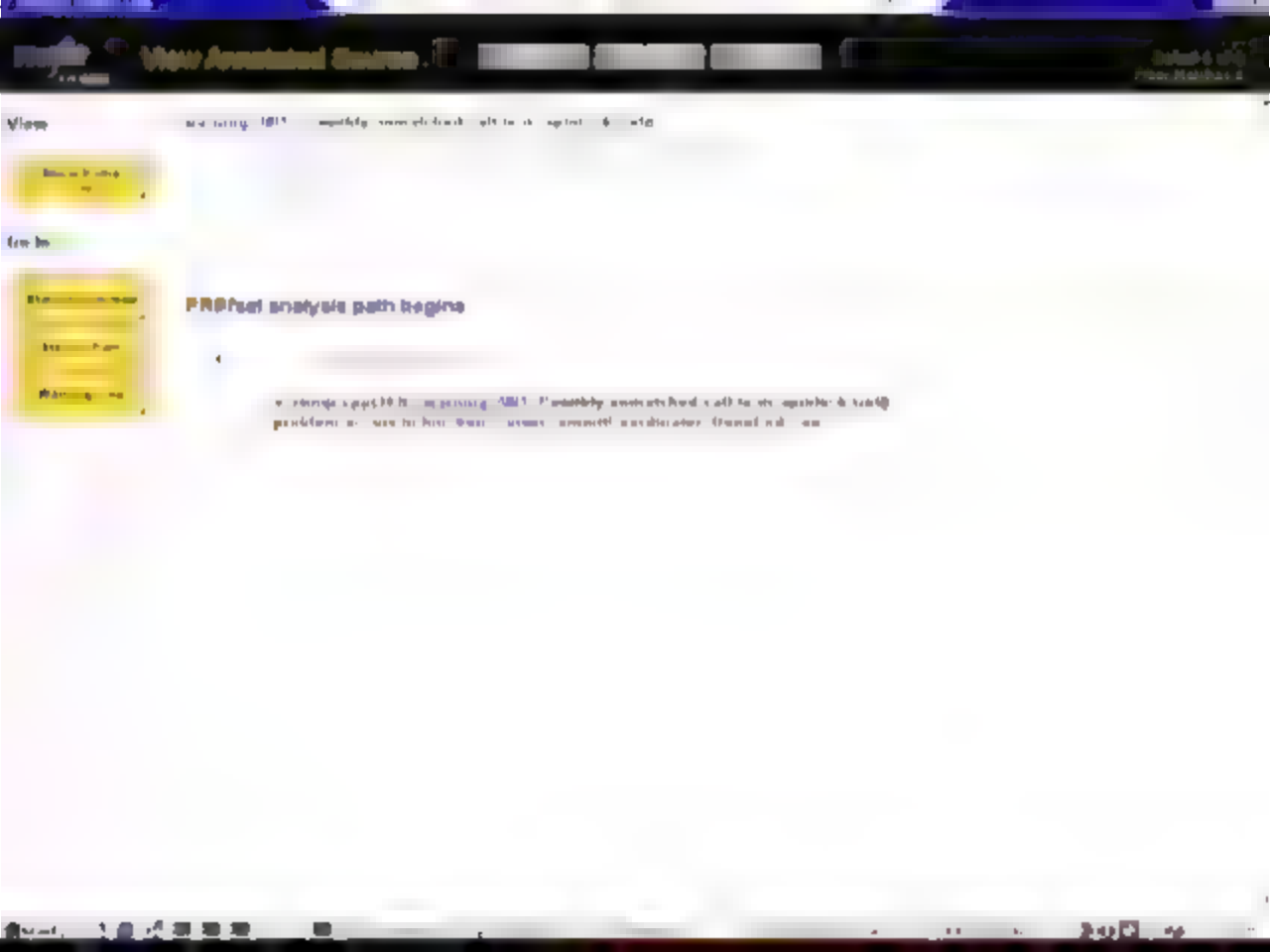


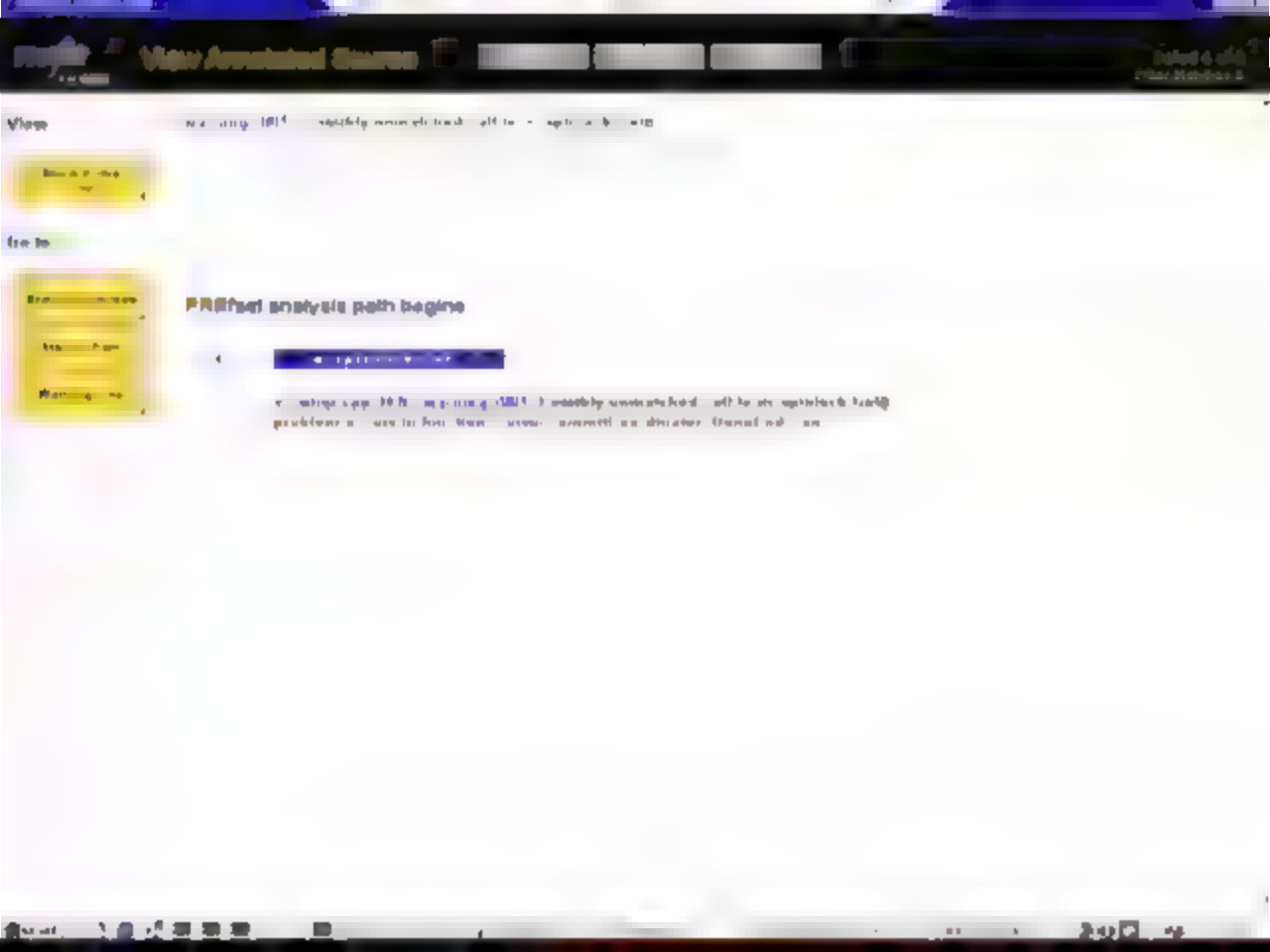


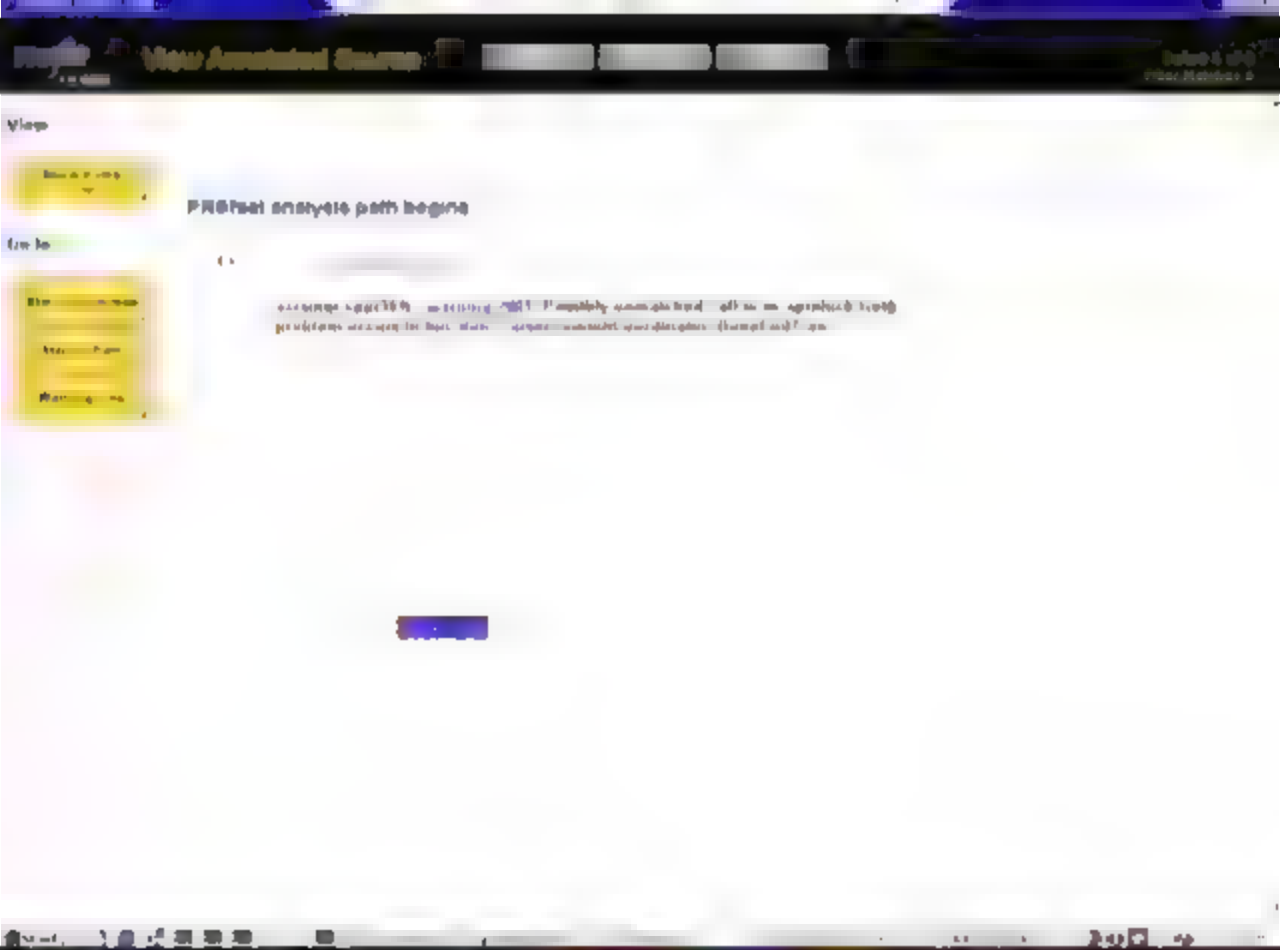
PREfast analysis path begins

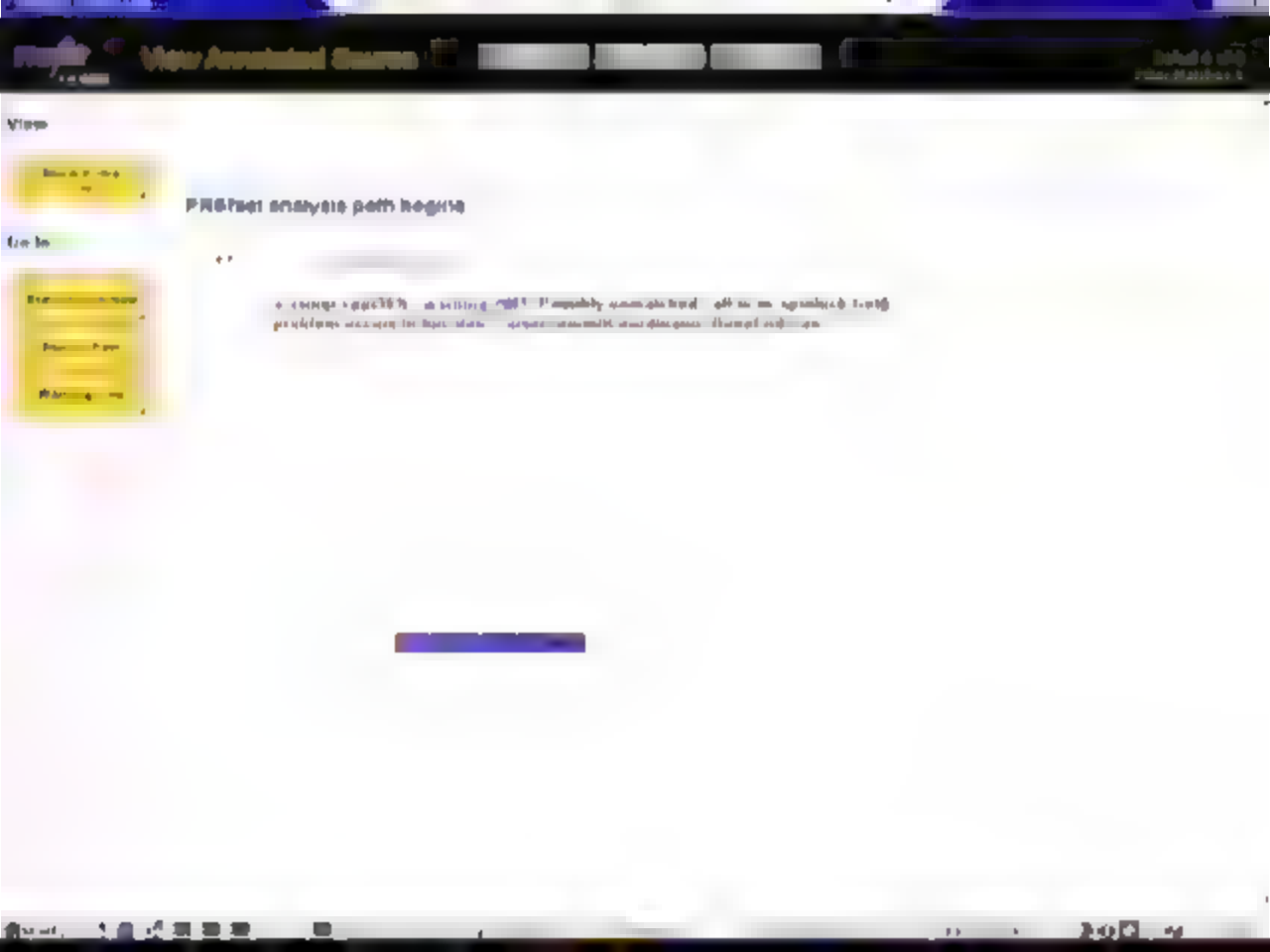


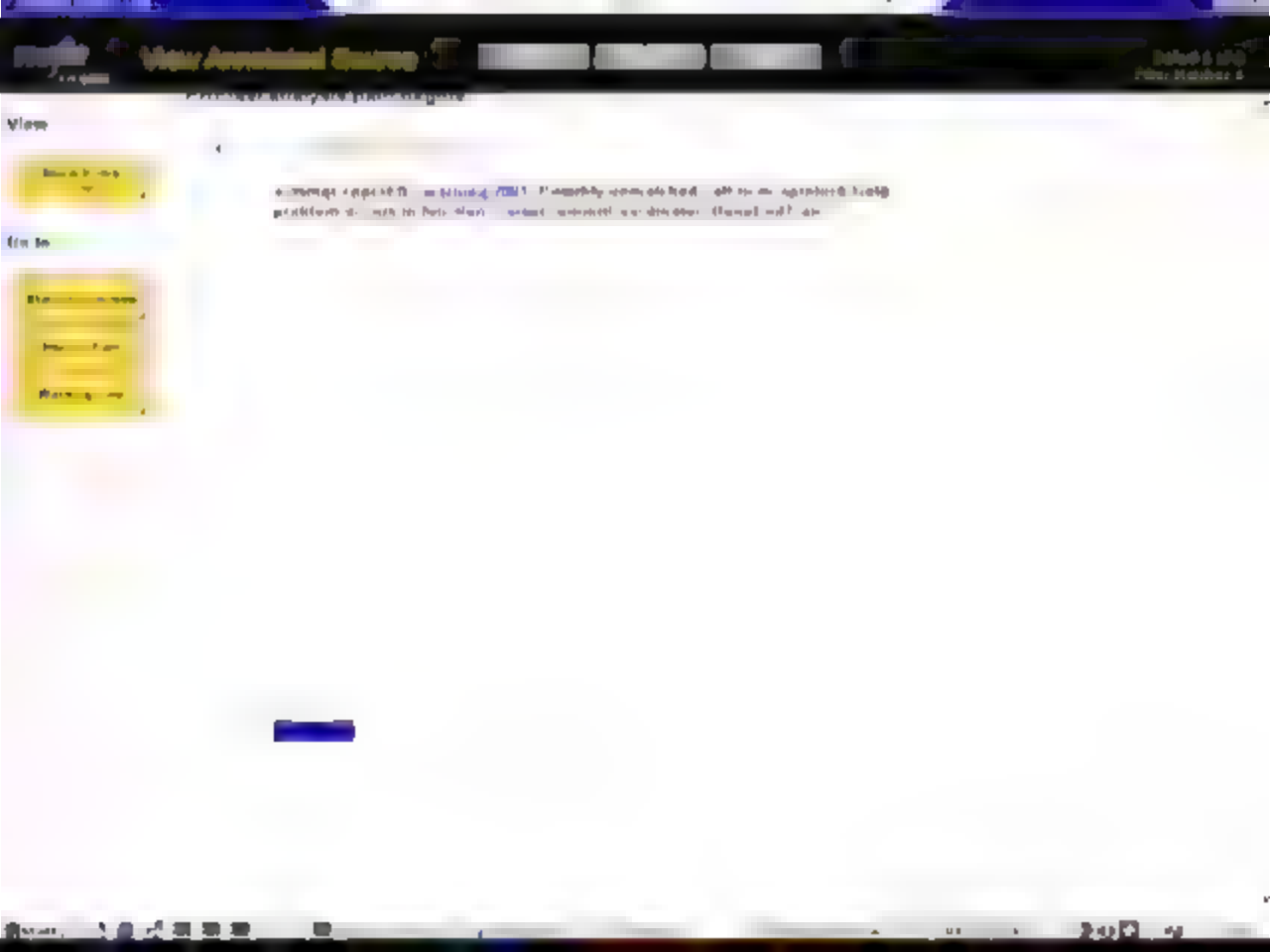












Concurrency

- Parallel and concurrent programs are hard to write, debug, test, modify, ...
  - Everyone is going to be writing many more of them
  - Cheap SMPs and .net
- Asynchronous programming
  - Message-passing (non-RPC) communication
  - Haskell++, Inega, ...
  - BizTalk
- Difficult behavioral properties
  - Deadlock-freedom
  - Communication progress
  - Message understood
- Few tools

Sharpie Example

```
// Declaration of client
operation client(in ch: x, out ch: w) @ x? => w!

// Implementation of server
server (in ch: z, out ch: y) @ z? => y!
{
  select z?() =>
    async c, d. client(c, d)
    in
      select d?() => y!
}
```

Sharpie Example

```
// Declaration of client
operation client(in ch: x, out ch: w) @ x? => w!

// Implementation of server
server (in ch: x, out ch: y) @ x? => y!
{
  select x?0 =>
    server.c.d.client(c, d)
  in
    select d?0 => y!
}
```

Sharpie Example

```
// Declaration of client
operation client(In ch: z, Out ch: w) @ z? -> w!

// Implementation of server
server (In ch: x, Out ch: y) @ x? -> y!
{
  select x?() ->
    async c, d, client(c, d)
    in
      select d?() -> y!
}
```

Receive on z
Send on w

Async call on client

Receive on d

Security Analysis

- Many security flaws exploit information flow

```
UserInput(s1);
...
CallToKernel(v);
```

- Value flow analysis
  - Determines where value comes from or goes to during execution
  - "Can the value of string s1 flow to variable v during execution?"
  - Previously, interprocedural analysis was imprecise or expensive

GOLF (Manuvir Das, Manuel Fahndrich, Jakob Rehof)

- Generalized One Level Flow
  - Whole-program value flow engine
- Scalable, context-sensitive, conservative analysis
  - Handles function calls accurately (context-sensitive)
  - Efficient (MLOC in seconds)
  - Precise (experimental evidence)
- Algorithms incorporated into PREfix
- Basis for family of security tools

SPT Summary

- SPT approach
  - Programmer/tester writes partial specifications
  - Tools ensure code follows specs
    - SLAM: extremely precise analysis
    - ESP: trade precision for scalability
    - Vault: integrate approach into language
    - Behave!: concurrency
    - GOLF: value flow problems
- Why so many projects?
  - Partial verification, not total correctness